SPECTRUM AND TRANSMISSION RANGE AWARE CLUSTERING FOR COGNITIVE RADIO AD HOC NETWORKS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

MAY 2018

I dedicate this work to

My beloved mother,

My Late father,

And

My sisters

ACKNOWLEDGEMENT

First, all praises and thanks be to Allah, without his blessing, guidance and mercy this work would never see the light. I would like to express my sincere gratitude and appreciation to my main supervisor, Associate Professor Dr. Sharifah Kamilah Syed Yusof for her patience, encouragement, guidance, and kindness. I would also like to thank my co-supervisor Dr. Nik Noordini Nik Abd Malik for her encouragement and advices. My profound gratitude goes to my beloved mother and my sisters for believing in me, for their love, prayers, and encouragement. My especial thanks to my friend, Aida Elrasheed, for her help and kindness during the initial settlement in UTM campus and afterward.

ABSTRACT

Cognitive radio network (CRN) is a promising technology to overcome the problem of spectrum shortage by enabling the unlicensed users to access the under-utilization spectrum bands in an opportunistic manner. On the other hand, the hardness of establishing a fixed infrastructure in specific situations such as disaster recovery, and battlefield communication imposes the network to have an ad hoc structure. Thus, the emerging of Cognitive Radio Ad Hoc Network (CRAHN) has accordingly become imperative. However, the practical implementation of CRAHN faced many challenges such as control channel establishment and the scalability problems. Clustering that divides the network into virtual groups is a reliable solution to handle these issues. However, previous clustering methods for CRAHNs seem to be impractical due to issues regarding the high number of constructed clusters and unfair load distribution among the clusters. Additionally, the homogeneous channel model was considered in the previous work despite channel heterogeneity is the CRN features. This thesis addressed these issues by proposing two clustering schemes, where the heterogeneous channel is considered in the clustering process. First, a distributed clustering algorithm called Spectrum and Transmission Range Aware Clustering (STRAC) which exploits the heterogeneous channel concept is proposed. Here, a novel cluster head selection function is formulated. An analytical model is derived to validate the STRAC outcomes. Second, in order to improve the bandwidth utilization, a Load Balanced Spectrum and Transmission Range Aware Clustering (LB-STRAC) is proposed. This algorithm jointly considers the channel heterogeneity and load balancing concepts. Simulation results show that on average, STRAC reduces the number of constructed clusters up to 51% compared to conventional clustering technique, Spectrum Opportunity based Clustering (SOC). In addition, STRAC significantly reduces the one-member cluster ratio and re-affiliation ratio in comparison to non-heterogeneity channel consideration schemes. LB-STRAC further improved the clustering performance by outperforming STRAC in terms of uniformity and equality of the traffic load distribution among all clusters with fair spectrum allocation. Moreover, LB-STRAC has been shown to be very effective in improving the bandwidth utilization. For equal traffic load scenario, LB-STRAC on average improves the bandwidth utilization by 24.3% compared to STRAC. Additionally, for varied traffic load scenario, LB-STRAC improves the bandwidth utilization by 31.9% and 25.4% on average compared with STRAC for non-uniform slot allocation and for uniform slot allocation respectively. Thus, LB-STRAC is highly recommended for multi-source scenarios such as continuous monitoring applications or situation awareness applications.

ABSTRAK

Rangkaian radio kognitif (CRN) adalah teknologi berpotensi untuk mengatasi masalah kekurangan spektrum dengan membolehkan pengguna yang tidak berlesen untuk mengakses jalur spektrum terkurang penggunaan secara oportunis. Selain itu, kesukaran untuk menubuhkan infrastruktur yang tetap dalam situasi tertentu seperti pemulihan bencana dan komunikasi medan perang memerlukan rangkaian yang mempunyai struktur ad hoc. Oleh itu, Rangkaian Ad Hoc Radio Kognitif (CRAHN) yang baharu muncul sewajarnya menjadi imperatif. Walau bagaimanapun, pelaksanaan praktikal CRAHN menghadapi banyak cabaran seperti penubuhan saluran kawalan dan masalah kebolehskalaan. Penggugusan yang membahagikan rangkaian kepada kumpulan maya adalah penyelesaian yang boleh dipercayai untuk menangani isu-isu ini. Walau bagaimanapun, kaedah penggugusan terdahulu untuk CRAHN seolah-olah tidak praktikal disebabkan oleh isu berkaitan jumlah tinggi bilangan gugusan yang dibina dan pengagihan beban tidak adil antara gugusan tersebut. Di samping itu, model saluran homogen telah dipertimbangkan dalam kajian terdahulu walaupun kepelbagaian saluran adalah ciri-ciri CRN. Tesis ini menangani isu-isu ini dengan mencadangkan dua skim penggugusan, iaitu saluran yang heterogen dipertimbangkan di dalam proses penggugusan. Pertama, algoritma penggugusan teragih yang dipanggil Penggugusan Sedar Julat Spektrum dan Transmisi (STRAC) yang mengeksploitasikan konsep saluran heterogen adalah dicadangkan. Di sini, satu fungsi pemilihan kepala gugusan yang baru dirumuskan. Satu model analisis diterbitkan untuk mengesahkan hasil STRAC. Kedua, bagi meningkatkan penggunaan lebar jalur, Penggugusan Sedar Julat Spektrum dan Transmisi Beban Seimbang (LB-STRAC) dicadangkan. Algoritma ini bersama-sama mempertimbangkan konsep keheterogenan saluran dan pengimbangan beban. Keputusan simulasi menunjukkan bahawa secara purata, STRAC mengurangkan bilangan gugusan yang dibina sehingga 51% berbanding teknik penggugusan konvensional, Penggugusan berasaskan Peluang Spektrum (SOC). Di samping itu, STRAC mengurangkan nisbah gugusan satu ahli dan nisbah gabungan semula dengan ketara berbanding skim pertimbangan saluran bukan heterogen. LB-STRAC selanjutnya meningkat prestasi penggugusan dengan mengatasi prestasi STRAC dari segi keseragaman dan kesaksamaan pengagihan beban trafik antara semua gugusan dengan peruntukan spektrum yang saksama. Selain itu, LB-STRAC telah terbukti sangat berkesan dalam meningkatkan penggunaan lebar jalur. Bagi senario beban trafik yang sama, LB-STRAC secara purata mempertingkatkan penggunaan lebar jalur sebanyak 24.3% berbanding STRAC. Di samping itu, untuk senario beban trafik yang berbeza-beza, LB-STRAC meningkatkan penggunaan lebar jalur sebanyak 25.4% dan 31.9% secara purata berbanding STRAC untuk peruntukan slot tidak seragam dan peruntukan slot seragam masing-masing. Oleh itu, LB-STRAC amat disyorkan untuk senario pelbagai sumber seperti penggunaan pemantauan berterusan atau penggunaan kesedaran situasi.

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LIST OF ABBREVIATIONS

AP	-	Affinity Propagation
CC	-	Control Channel
CCC	-	Common Control Channel
CDMA	-	Code Division Multiple Access
CH	-	Cluster Head
CHDF	-	Cluster head Determination Factor
CR	-	Cognitive Radio
CRAHN	-	Cognitive Radio Ad Hoc Network
CRN	-	Cognitive Radio Network
CRB	-	Cognitive Radio Base station
CRT	-	Cognitive Radio Terminal
CRSN	-	Cognitive Radio Sensor Network
CV	-	Coefficient of Variation
DSA	-	Dynamic Spectrum Access
DS	-	Dominant Set
DCA	-	Distributed Clustering Algorithm
IEEE	-	Institute of Electrical and Electronics Engineers
ISM	-	Industrial, Scientific and Medical
FCC	-	Federal Communications Commission
GUI	-	Graphic User Interface
HetCh	-	Heterogeneous Channel
HomCh	-	Homogenous Channel
KM	-	KiloMeter
LAN	-	Local Area Network
LB	-	Load Balancing
LCCC	-	Local Common Control Channel

MANET	-	Mobile Ad hoc Network
MCMR	-	Multi-Channel Multi Radio
MDS	-	Minimum Dominant Set
MEB	-	Maximum Edge Biclique
MEBC	-	Maximum one side Edge Cardinality Biclique
MNB	-	Maximum Node Biclique
MPC	-	Multiple Primary user Channel
MRCC	-	Multiple Rendezvous Control Channel
OSA	-	Opportunistic Spectrum Access
PU	-	Primary User
RF	-	Radio Frequency
ROSS	-	RObust Spectrum Sharing
SABC	-	Spectrum Aware Based Clustering
SDR	-	Software Defined Radio
SF	-	Selection Factor
SMART	-	SpectruM-Aware clusteR-based rouTing
SOC	-	Spectrum Opportunity based Clustering
SPC	-	Single Primary user Channel
STRAC	-	Spectrum Transmission Range Aware Clustering
SU	-	Secondary user
TDMA	-	Time Division Multiple Access
TR	-	Transmission Range
TV	-	TeleVision
VANET	-	Vehicular Ad Hoc Network
UWB	-	Ultra Wide-Band
Wi-Fi	-	Wireless Fidelity
WIMAX	-	Worldwide Interoperability for Microwave Access
WSN	-	Wireless Sensor Network

LIST OF SYMBOLS

N	-	Number of secondary users
M	-	Number of target channels
L	-	Channel type number
r_l	-	Transmission range of type l channel
r_{max}	-	Maximum transmission range
C_i	-	Set of available channel for su_i
M_i	-	Number of available channels for su_i
D_{im}	-	The distance between su_i and pu_m
d_{ij}	-	The distance between su_i and su_j
C_{ij}	-	A set of common channel between su_i and su_j
N_i	-	Set of 1-hop neighbour for su_i
N_{ic}	-	Set of 1-hop neighbour for su_i in channel c
P_{idle}	-	Probability of licensed channel to be idle
SF_i	-	Selection factor for su_i
CH_i	-	Cluster head i
CL_i	-	Set of member of cluster i
$CLCC_i(I)$	-	Set of ccs between the CH_i and its members at iteration I
K	-	Minimum channel threshold per cluster
PL_j	-	Potential CHs set for su_j
$Load_i$	-	Potential load of CH_i
C^l	-	A set of type l channels
B	-	Control message length in bits
$E_{tx}(B,d)$	-	Energy consumption to transmit b bits
E_{elec}	-	Consumed energy in the transmitter or receiver circuitry
E_{amp}	-	Consumed energy in the transmitter amplifier

E_{rx}	-	Energy consumption to receive B bits
R^m	-	Channel reward vector
V^{ij}	-	Common channel availability vector of su_i, su_j
${v_m}^{ij}$	-	Common channel availability vector element of su_i, su_j
${c_m}^{ij}$	-	Channel availability vector element of su_i, su_j
l^{ij}	-	Link robustness vector of su_i, su_j
${l_m}^{ij}$	-	Link robustness vector element of su_i, su_j in m^{th} channel
L_{ij}	-	Relative link robustness of su_i, su_j
L_i	-	Cumulative link robustness of su_i
$CLCC_i$	-	Custer i common channels set
P	-	Probability of channel to be available
P_l	-	Probability of channel type l be available
R_l	-	Protection range of type l channel
P_{lav}	-	Probability of link availability
${P_{l,L}}^{1,2}$	-	Probability of the of at least one channel from types l to l available between two SUs
$P_{cc,2}$	-	Probability of availability of a single channel of type $l\ to\ L$between two SUs.
$\overline{P_{cc,2}}$	-	Complement probability of $P_{cc,2}$
$\overline{P_{cc,2,m_l}}$	-	Probability there is no any available cc of type l among m_l channels between two SUs
$\overline{P_{cc,2,M}}$	-	Probability there is no any available CC of type l among M channels between two SUs
${P_{cc,2,M}}^1$	-	Probability of the existence of at least one CC available between two secondary users among M channels
$E[Z]$	-	Expected cluster size
$E[D]$	-	Expected number of neighbours
P_{join}	-	Probability of neighbours to fulfil the clustering requirements
$P_{K,l,L}$	-	Probability of at least K channels from types l to l common between any ch and its neighbours
$P_{area,l}$	-	Probability all expected neighbours to be inside a_l

$P_{cc,D1}$	-	Probability of a single type l channel to be available to any CH and its expected neighbours ($E[D]$)
$P_{l,L}$	-	Probability of a channel from type $l\ to\ L$ be available for any CH and its neighbours
$\overline{P_{area,l}}$	-	Probability of at least one neighbour to be outside a_l
P_{total}	-	Total probability of channel availability
$P_{av,l}$	-	Probability of any channel to be available and from type l
$E[CL\_No]$	-	Expected cluster number
$D_{upper,l}$	-	The upper value of $E[D]$
$E[CCCL]$	-	Expected number of common channels per cluster
P_{cccl}	-	Probability of common channels per cluster
$P_{CL\_area,L}$	-	Probability of all cluster members to be inside a_l
$P^{l,L}$	-	Probability of the channel to be of type $l\ to\ L$
$P_{l,CL}$	-	Probability of channels of type $l\ to\ L$ to be available and common in each cluster
${P_{l,L}}^{K,CL}$	-	Probability of at least K channels of types $l\ to\ L$ are common between all members in each cluster
$Rank_{ij}$	-	Rank value of su_j in cluster i
$\overline{PL_J}$	-	Set of claiming clusters in which su_j has the same rank value
λ	-	Average connections generation rate
μ	-	Mean of connection duration

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CHAPTER 1

INTRODUCTION

1.1 Background

Static spectrum apportionment policies eliminate interference between various wireless technologies by separating their operating frequency. However, the static apportionment policy has caused a spectrum shortage. As a result, modern wireless services and technologies have struggled to survive in congested, uncontrollable interference unlicensed bands such as the industrial, scientific and medical (ISM) bands. On the other hand, it has been found out that, a huge amount of the licensed spectrum is extremely underutilized [1, 2]. In order to handle the spectrum shortage problem, a new policy, that permits unlicensed users to opportunistically use unoccupied licensed spectrum, is presently being endorsed by the Federal Communications Commission (FCC) [1, 2]. Consequently, opportunistic spectrum access (OSA) techniques and cognitive radio technology are introduced as smart wireless communication technologies that enabling the cognitive radio (CR) also called the secondary users (SUs) to access the license bands in opportunistic manner. However, the feature brought by CR technology introduces spectrum management and network coordination challenges. Precisely in cognitive radio ad hoc networks(CRAHNs), the distributed multi-hop architecture.

Recently, CRAHNs has gained a great interest in the research community. This is due to its valuable role in situations, where the infrastructure network is neither available nor economical to establish, such as battlefield communication and disaster relief [3]. However, the absence of infrastructure and rapid topology changes inherit from the wireless ad hoc network, along with the intrinsic feature of cognitive radio networks (CRNs), known as the dynamicity of channel availability, present unprecedented challenges that hinder the practical implementation of CRAHNs. The most critical challenges can be abstracted as following:

Control channel (CC) assignment is one of most critical challenge facing the cognitive radio ad hoc networks. As illustrated in Figure 1.1, the challenge arises in the following two aspects:

i. Spectrum heterogeneity, secondary users (SUs) usually observe different sets of available channels. So, it is improbable to find a channel available to all SUs. However, SUs in same neighbourhood do share a significant number of available channels. Hence, different channels have to be assigned for control in different neighbourhood [4],[5].

ii. Primary user (PU) activity, unless the CC allocated in frequency band free from PUs (out-band), the CC is susceptible to PU activity and can be occupied by PUs at any time [4, 5].

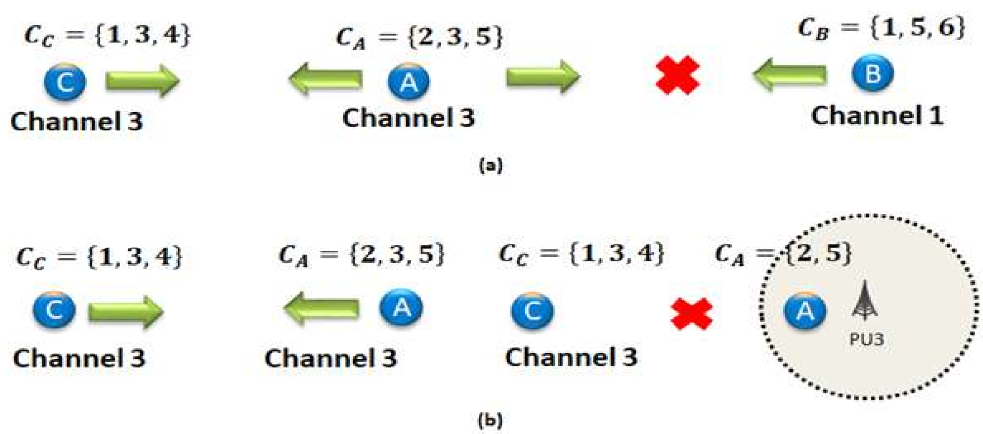

Figure 1.1: Control Channel Assignment Issues (a) Spectrum Heterogeneity.(b) Primary User (PU) Activity.

Another critical challenge, CRAHNs encounters scalability problems with increased network size, resulting from routing difficulties as well as congestion from flooding. Routes might have to recomputed and updated in entire network even if only a small number of SUs changed their locations. So routing protocol based on flat network become infeasible because of high protocol overhead [6]. Hence a method to scale down the network is needed.

Clustering is a reliable solution to address the aforementioned challenges. Clustering is topology management technique that efficiently improves the performance of the network by dividing the flat ad hoc network into virtual groups according to specific rules. These rules are determined based on the purpose of clustering.

In CRAHNs grouping the SUs into clusters according to the similarity of their available channels, solve the problem of control channel assignment. Furthermore, in cluster based networks only few users (cluster heads and gateways) participate in finding routes, which greatly reduces the routing table size and the number of necessary broadcasts. In addition, the clustered structure make the network appear smaller and more stable in the view of each user, since any change in network topology only need to be updated locally. Designing a clustering scheme that considers the spectrum availability known as spectrum-aware clustering [5].

Although a number of researchers have proposed spectrum-aware clustering design schemes for CRAHNs in order to support the network management and fix the problem of control channel assignment [5, 7-14]. However, these schemes seem to be unpractical due to the lack of the consideration of the heterogeneous nature of the channels in term of transmission ranges. Moreover, these schemes ignored the needing of a fair distribution of traffic load among the constructed clusters so some of these clusters will be overcrowded which will lead to unfairness spectrum allocation and poor bandwidth utilization specifically if it adopted in multi-source scenarios such as continuous monitoring applications or situation awareness applications.

1.2 Problem Statement

In order to efficiently constructed cluster based network to solve the problem of control channel and support the scalability in CRAHNs two issues need to be addressed namely heterogeneous channels transmission ranges and the load balance among clusters. In this respect, the problems addressed in this thesis are as follows:

As depicted in Figure 1.2, unlike the traditional multi channels network in which all channels have homogeneous transmission ranges, the CRAHNs introduces the heterogeneous transmission ranges issue. That is because the targeted (observed) channels may be located on separated bands with different propagation characteristics. Also, FCC regulations define different transmission ranges for different channels [15-17] . Moreover, considering a constant transmission range for the secondary users is unacceptable due to the following. First, using a fixed transmission range in all channels will eliminate the distinguishing feature of SUs: interacting and adapting with the surrounding environments [18]. Second, the value of the radio communication range has significant impact on the network connectivity. Using the longest channel transmission range as common transmission range in all targeted channels improves the connectivity by increasing the number of direct connections but it against FCC regulations. On the other hand, using the shortest channel transmission range as common transmission range decreases the connectivity. So, while considering the channel heterogeneity, what is the best way of development clustering scheme that solve the problem of CC and ensures network stability (large number of common channels per cluster) while increasing the network scalability (small clusters number)?

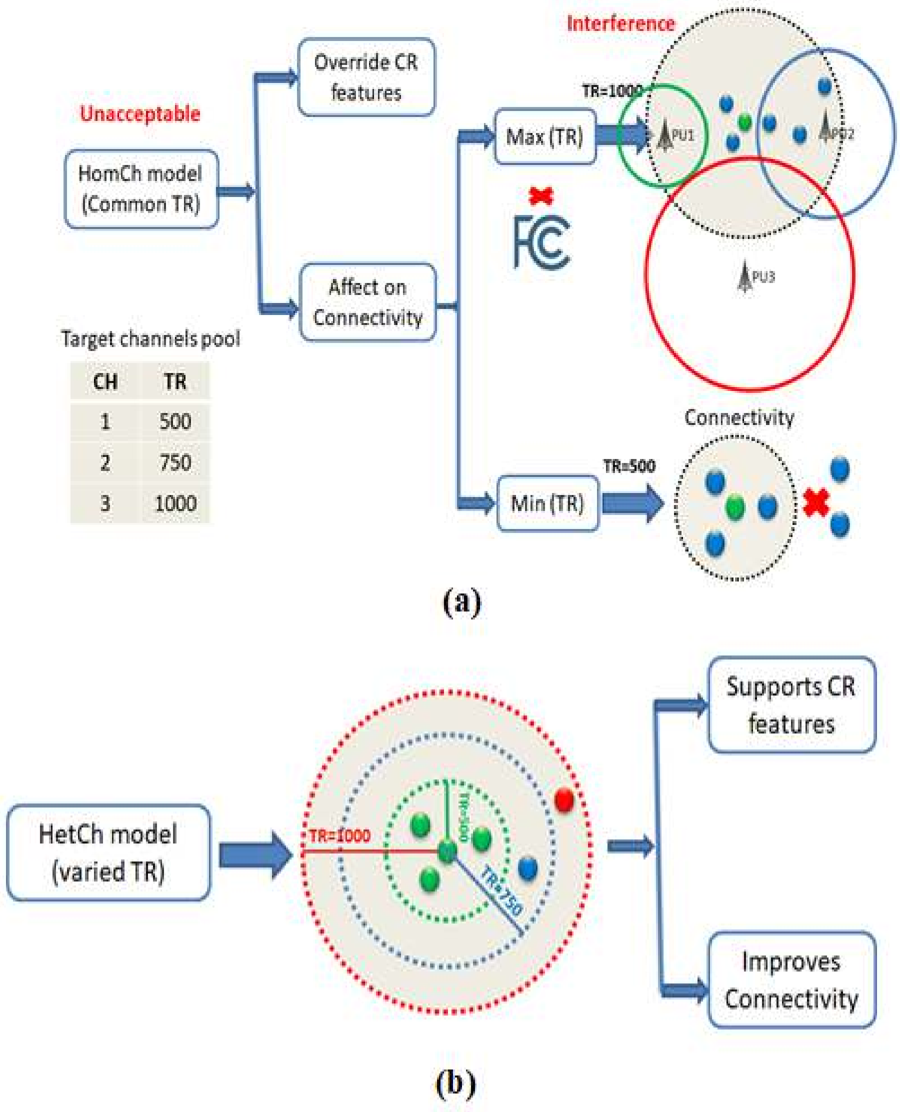

Figure 1.2: Cognitive Radio Channel Models Scenarios (a) Homogeneous Transmission Ranges.(b) Heterogeneous Transmission Ranges.

Additionally, in traditional clustering schemes the normal secondary users usually join the neighbouring cluster head which have the best feature with reference to the used metric for clustering [7, 13]. This attitude causes some clusters to be overcrowded while other may have only one member. Recalling the inverse relationship between the cluster size and the number of common channels per cluster [5, 13, 19], overcrowded clusters means large number of secondary users share a small amount of bandwidth for intra-clustering communication which causes traffic congestion. While the small size clusters have more bandwidth than their needs. This results in misuse of available bandwidth which will consequently affect the performance of cluster based network negatively. Thus, the question arises on finding a reliable way of distributing the load (secondary users) among the clusters that would lead to bandwidth utilization improvement.

1.3 Objectives of the Thesis

The aim of this thesis is to develop an efficient clustering scheme that facilities the practical implementation of CRAHNs. This goal is achieved by considering both the channel heterogeneity and load balancing concepts during clustering formation process. The specific objectives of the research are:

i. To design and develop spectrum and transmission range aware clustering technique (STRAC) for CRAHN that establishes a local common control channel and supports the network scalability.
ii. To investigate the impact of heterogeneous channel transmission ranges in the clustering performance.
iii. To design and develop a load balancing mechanism during clustering process (LB-STRAC) in order to enhance the bandwidth utilization.
iv. To evaluate and validate the simulated results based on the performance metrics.

1.4 Scope of the Research

This research focuses on the design of clustering formation algorithms in cognitive radio ad hoc networks (CRAHNs). This work attends to design new clustering algorithms by integrating the cognitive features, channel heterogeneity and load balancing concepts to enhance the clustering performance. These algorithms mainly concern with the situation at the initialization of the network.

In this research CRAHN that co-exists with primary user network is considered. Here, the availability of the channels to secondary users is determined based on their proximity to the primary user of that channel and its activities on it. Each secondary user determines its available channels set independently where the targeted spectrum band is composed of finite number of channels. These channels are assumed to have different transmission ranges.

The proposed clustering algorithms work in a distributed manner based on local information. Specifically, each secondary user is assumed to acquire knowledge of its 1-hop neighbours through the neighbour discovery process which is out of scope of this thesis. The proposed clustering formation algorithms are developed based on the snapshot of network. Thus, the channel availability information and secondary user's location do not change during cluster formation process. Moreover, multi-source network scenario where each secondary user is a data source is considered.

1.5 Research Contributions

In a bid to achieve the proposed objectives, this work made the following contributions:

i. In order to achieve the first and second objectives, a novel spectrum-aware clustering algorithm based on the channel heterogeneity named Spectrum and Transmission Range Aware clustering (STRAC) is developed. STRAC is an efficient algorithm for solving the CC problem in CRAHNs and enhancing the network scalability. In addition to STRAC being a new algorithm for clustering in CRAHNs, it exploits the heterogeneity of channels in term of transmission range to further enhance the clustering performance. Here, a new metric for the cluster head selection called selection factor which is calculated based on the number of neighbours, the number of common channels with neighbours, the number of available channels, and the available channels coverage is provided.

ii. To validate the STRAC performance a mathematical model is developed. This model characterizes the channel availability in CRAHNs. This model also provides mathematical expressions for the probability of channel availability, probability of link availability, expected number of neighbours, expected cluster size, expected number of clusters and expected number of common channels per cluster.

iii. To achieve the third objective, Load Balance Spectrum and Transmission Range Aware clustering (LB-STRAC) algorithm that alleviates the non-uniformity of load distribution among the clusters is developed. LB-STRAC is a distributed clustering algorithm that jointly considers the channel heterogeneity and load balancing concepts to further improve the efficient of constructed cluster based network by enhancing the bandwidth utilization.

1.6 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2, presents a critical review on the available literature related to the scope of this thesis. It discusses on the cognitive radio networks taking into account the cognitive radio technology concept, CRNs Architecture and spectrum access techniques. Moreover, in this chapter, the control channel assignment techniques in CRAHNs are elaborated. Clustering is critically reviewed in this chapter; a brief background on clustering and different situations where clustering is used in ad hoc network are provided. Then, a detail discussion on clustering in CRAHNs is carried out, including the benefits of clustering in CRAHNs, the approaches for modelling clustering formation problem, the performance metric, the techniques that are utilized for clustering and the classification of clustering algorithms. Finally, related works are presented.

Chapter 3 presents an overview of the proposed framework used throughout the thesis and the methodology perused in accomplishing the proposed objectives. First, an overview of the channel heterogeneity concepts is presented. Then, the adopted network model and assumptions are stated. Afterwards, the fundamental steps of development and implementation of proposed clustering algorithms are explained. Finally, the evaluation setup and the evaluation metrics were stated.

Chapter 4 explains the STRAC algorithm to establish control channel for CRAHNs and enhance the network scalability. The operational modules of STRAC along with implementation method are introduced. A mathematical model for STRAC is then derived to emulate the behaviour and features of STRAC, and validate its outcomes. Afterwards, the performance evaluation results of STRAC which includes, the results of the validation of STRAC with its analytical model, the effect of the channel heterogeneity on the clustering performance results, the results of the effect of the number of PUs on STRAC performance, and comparison results with similar algorithms from literature are presented.

Chapter 5 presents LB-STRAC algorithm to enhance the bandwidth utilization. First, it demonstrates the detail of implementation of the proposed LB-STRAC. Then, it presents the performance evaluation, including how the results were obtained and the discussion of the results.

Chapter 6 summarizes the work that has been done in this thesis, restating the research objectives and the contributions made in order to achieve the proposed objectives. Lastly, suggestions on the directions for future work are mentioned.

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