Doctor of Philosophy (PhD) Thesis
Université Pierre & Marie Curie - Sorbonne Universités

Specialization

COMPUTER SCIENCE

presented by

Mubashir Husain Rehmani

Submitted for the partial requirement of

Doctor of Philosophy
from
Université Pierre & Marie Curie (UPMC) - Sorbonne Universités

Opportunistic Data Dissemination in Ad-Hoc Cognitive Radio Networks

12th Dec 2011

Commitee:

Jean-Marie Gorce	Reviewer	Professor, INSA-Lyon - France
Thierry Turletti	Reviewer	Researcher, INRIA - Sophia Antipolis - France
Hakima Chaouchi	Examiner	Professor, Institut Télécom SudParis - France
Pierre Sens	Examiner	Professor, UPMC - Sorbonne Universités – Paris - France
Hicham Khalife	Examiner	Assistant Professor, LaBRI/ENSEIRB – Bordeaux - France
Aline Carneiro Viana	Advisor	Research Scientist, INRIA – Saclay - France
Serge Fdida	Director	Professor, UPMC - Sorbonne Universités – Paris - France

Thèse de Doctorat (PhD) de
l'université Pierre & Marie Curie - Sorbonne Universités

Spécialité

SYSTÈMES INFORMATIQUES

présentée par

Mubashir Husain Rehmani

pour obtenir le grade de

Docteur de l'université Pierre & Marie Curie (UPMC) - Sorbonne Universités

Dissémination Opportuniste de données dans les réseaux ad-hoc à radio cognitive

12th Dec 2011

Jury composé de :

Jean-Marie Gorce	Rapporteur	Professor, INSA-Lyon - France
Thierry Turletti	Rapporteur	Researcher, INRIA - Sophia Antipolis - France
Hakima Chaouchi	Examinateur	Professor, Institut Télécom SudParis - France
Pierre Sens	Examinateur	Professor, UPMC - Sorbonne Universités – Paris - France
Hicham Khalife	Examinateur	Assistant Professor, LaBRI/ENSEIRB – Bordeaux - France
Aline Carneiro Viana	Encadrant	Research Scientist, INRIA – Saclay - France
Serge Fdida	Directeur	Professor, UPMC - Sorbonne Universités – Paris - France

Dedication

To my Dearest Mother
and
To my Sheikh.

Acknowledgements

First and foremost, I am thankful to Allah Subhanahu wa-ta'ala that by His grace and bounty, I am able to write my PhD thesis. I ask sincerity in all my actions from Allah Subhanahu wa-ta'ala and I quote the verse from the Holy Quran "*Say, .My prayer, my offering, my life and my death are for Allah, the Lord of all the world*" (Surat Al-'An'am, verse 162).

I wish to express my sincere gratitude to the Reviewers, Professor Jean-Marie Gorce, from INSA-Lyon, France and Full Time Researcher, Thierry Turletti, from INRIA - Sophia Antipolis - France, for their useful reviews and suggestions that really improved the quality of the manuscript. I am grateful to Professor Hakima Chaouchi, Professor Pierre Sens and Assistant Professor Hicham Khalife to be the part of the Jury selected for my thesis defense. Hicham Khalife's thought provoking suggestions helped me a lot during my thesis.

I am deeply indebted to my supervisor Aline Carneiro Viana, whose professional suggestions and guidance helped me in my research work. I want to mention that Aline was also my Master's Thesis supervisor. We passed a long journey together, which is almost four years. She always thought about my prosperity and welfare. She always helped me when I was stuck in research and administrative issues. Whatever I have learnt in my research, it is because of her invaluable teachings. I pray for her prosperity and happiness.

I deeply acknowledge Professor Serge Fdida (a great source of inspiration for my research) for his generous support which helped me a lot to finish my PhD thesis. I also want to mention the name of Marguerite Sos, who helped me in administrative issues in the university. I gratefully acknowledge the funding provided by Higher Education Commission (HEC), Government of Pakistan, and partial funding provided by Professor Serge Fdida. I want to mention the support provided by my person in-charge in SFERE, Somia Ashraf, to whom, i am extremely thankful. I am grateful to Martin May and Thi Mai Trang Nguyen for their precious advice on the mid-term review of my thesis.

I wish to express gratitude to my Sheikh, Mufti Mohammed Naeem Memon of Hyderabad, Pakistan (Caliph of Maulana Muhammad Yousuf Ludhianyvi Shaheed), I could not have done my PhD without his prayers, spiritual guidance and moral support.

Many thanks to Muhammad Afraz, who helped me to keep in touch with my Sheikh. I also want to mention the name of Mohammed Younus Memon, Mufti Taqi Usmani, Maulana Hakim Akhtar Sahib, who gave me very precious advices.

I spent first year of PhD in ASAP, INRIA, Saclay, France. During that period, I spent my time with Massimo Vecchio, Golnaz Karbaschi, Marie-Jeanne Gaffard, and Fabrice Lefessant, to whom I am grateful. I then moved to Lip6, UPMC, where I spent more than 2 years, until the PhD thesis defense. I want to thank my office mates : Tuan-Minh Pham, Raul Adrian Gorcitz, Asim Ali, and Fabio Rocha Jimenez Jimenez Vieira. I can not forget the great time I spent in my lab with Mohamed Diallo, Mehdi Bezahaf, Nadjet Belblidia, Adisorn Lertsinsrubtavee, and Marcelo Dias de Amorim.

My special thanks to Nadeem Javaid, Ayaz Ahmed, Zeeshan Ali Khan, Abdul Wahid Memon, Usama Mir, Muhammad Zahid, Salman Atif, Taj Muhammad Khan, Khalil Laghari, Saim Abdul Ghafoor, Zahir Ali Shah, Farrukh Saleem, Junaid Iqbal, Rahat Ali Awan and Shujaat Ali Awan. I want to mention the names of Huseyin Dogan, Hassan Dogan, and Iqbal Masood Khan for their kind wishes. I want to thank Madam Neelofar Rehman who taught me French Language in Karachi.

My brothers-in-arms are Muhammad Muzzamil Luqman, Muhammad Shoaib Saleem, Yasir Faheem, and Farhan Mirani. Shoaib always prayed for my success, and Farhan always refreshed my mind with his fresh thoughts. I am thankful to Yasir for all the gatherings he arranged in the leisure time to boost my optimism for my research work. Muzzamil's encouragement helped me a lot to excel my programming skills which was a crucial phase during my research.

The help of Ahlem Reggani for the translation of the French version of the thesis summary is unforgettable. I am extremely thankful to her for being so kind with me.

Manel Khelifi has been helping me a lot. She read my papers for feedback purpose. She helped me whenever I faced difficulty for the draft written in French. With a very short notice of time, she helped me in the French translation of the thesis summary. I have no words to express my sincere thanks to her.

Finally, I want to thank to my family members : Abbu, Aapa ji, Farah Baji, Humera Baji, Haroon Bhai, Faiza Baji, Mudassir, Jilani Bhai, Asfa, Absar, Faseeh and Mohibuddin, for all their love, patience, and encouragement. While finishing my final manuscript and writing these lines, I really miss my mother. May Allah Subhanahu wa-ta'ala increase her darajaat in Jannat, aameen.

Mubashir Husain Rehmani
06^{th} Oct 2011

Abstract

Recent advances in communication technologies and the proliferation of wireless computing and communication devices make the radio spectrum overcrowded. However, experiments from the Federal Communication Commission (FCC) reveals that the spectrum utilization varies from $15\% - 85\%$. Consequently, Cognitive Radio Networks (CRNs) are proposed to utilize the radio spectrum opportunistically.

In types of cognitive radio networks where channels for transmission are opportunistically selected – also called Cognitive Radio Ad-Hoc Networks –, reliability in data dissemination is difficult to achieve. First, in addition to the already known issues of wireless environments, the diversity in the number of channels that each cognitive node can use adds another challenge by limiting node's accessibility to its neighbors. Second, Cognitive Radio (CR) nodes have to compete with the Primary Radio (PR) nodes for the residual resources on channels and use them opportunistically. Besides, CR nodes should communicate in a way that does not disturb the reception quality of PR nodes by limiting CR-to-PR interference. Therefore, a new channel selection strategy is required which cause less harmful interference to PR nodes and try to maximize the chances that the message is delivered to the neighboring cognitive radio receivers, thus increasing the data dissemination reachability.

In this thesis, we propose SURF, a distributed channel selection strategy for robust data dissemination in multi-hop cognitive radio ad-hoc networks. SURF classifies the available channels on the basis of primary radio unoccupancy and the number of cognitive radio neighbors using the channels. Simulation results in NS-2 confirmed that SURF is effective in selecting the best channels for data dissemination, when compared to related approaches. We observe that the channel selection strategies are greatly influenced by the primary radio nodes activity. Next in this thesis, we study and analyze the impact of PR nodes activity patterns on different channel selection strategies through NS-2 based simulations. We observed that intermittent PR activity is the case where clever solutions need to operate. This is where SURF gives the best results and the target region to avail communication opportunities.

Finally, in this thesis, we go one step further and check the applicability and feasibility of SURF. In this perspective, first we propose a cognitive radio based Internet access framework for disaster response networks. We discuss the architectural details and the working principle of the proposed framework. We highlight the challenges and issues related with the deployment and connectivity of the framework. Second, we discuss the applicability of SURF in the context of channel bonding and in this regard, we discuss an interference based channel bonding strategy for cognitive radio networks.

Keywords

Cognitive radio networks, data dissemination, channel selection, dynamic spectrum access networks, disaster response network, Internet access framework.

Résumé

Les progrès récents des technologies de communication et la prolifération de l'informatique sans fil et des dispositifs de communication, ont induit à une surcharge dans l'utilisation du spectre radio. Cependant, les expériences de la Commission Fédérale de Communication (FCC) ont révélé que l'utilisation du spectre varie entre 15% et 85%. Par conséquent, les réseaux radios cognitifs (Cognitive Radio Networks ou CRNs) sont proposés afin d'utiliser le spectre radio d'une manière opportuniste.

Dans ce type de réseaux radios cognitifs, où les fréquences de transmission sont sélectionnées d'une manière opportuniste - également sont appelés réseaux Ad-Hoc à radios cognitives -, la fiabilité de la dissémination des données est difficile à réaliser. D'abord, en plus des défis déjà connus dans les environnements sans fils, la diversité dans le nombre de fréquences qu'un nœud à radio cognitif a droit d'utiliser ajoute un autre défi, en limitant l'accessibilité à ses nœuds voisins. Deuxièmement, les nœuds à radio cognitif (CR) doivent conquérir les ressources de fréquences résiduelles avec les nœuds à radio primaire (PR), tout en essayent de les exploiter d'une manière opportuniste. En outre, les nœuds CR ne devraient pas perturber la qualité de réception des nœuds PR durant leur communication, et ce en limitant les interférences entre les deux de nœuds. Par conséquent, une nouvelle méthode de sélection de fréquences est requise afin de réduire le nombre d'interférences nuisibles aux nœuds PR, et maximiser les chances de délivrance des messages aux voisins récepteurs des nœuds CR, et augmenter ainsi la fiabilité des données disséminées.

Dans cette thèse nous proposons SURF, une nouvelle méthode distribuée de sélection de fréquences pour la dissémination fiable de données dans un réseau radio cognitif multi-sauts. SURF classifie les fréquences radio disponibles en fonction de l'occupation des fréquences des nœuds à radio primaire et le nombre de noeuds à radio cognitive utilisant ces fréquences. Les résultats de simulation obtenus par NS-2 confirment que SURF est une stratégie efficace dans la sélection des meilleures fréquences de diffusion de données, comparée aux autres approches liées. Nous avons aussi constaté que les stratégies de sélection de fréquences sont considérablement influencées par l'activité des nœuds à radio primaire. Dans la suite ce cette thèse, nous étudierons et analyserons l'impact des modèles d'activités des nœuds PR sur les différentes stratégies de sélection de fréquences à travers des simulations basées NS-2. Nous avons remarqué que l'activité intermittente de PR est le cas où les solutions intelligentes doivent opérées. C'est dans ce cas où SURF donne les meilleures résultats et la région ciblée se serve des opportunités de communication.

Enfin, dans cette thèse, nous allons encore plus loin en vérifiant l'applicabilité et la faisabilité de SURF. Dans cette perspective, d'abord, nous proposons une architecture d'accès à internet basée sur la radio cognitive pour les réseaux partiellement endommagés. Nous discutons les détails architecturaux et le principe de fonctionnement de l'architecture proposée. Nous avons également passé en revue les enjeux et les défis de déploiement de cette nouvelle architecture. Deuxièmement, nous discutons l'applicabilité de SURF dans le contexte de l'agrégation de fréquences et à cet égard, nous discutons une stratégie d'interférence basée sur l’agrégation de fréquences pour les réseaux radios cognitifs.

Mots-clés

Réseaux radio cognitifs multi-sauts, sélection dynamique de fréquence, dissémination de données, environnement hostiles, architecture d’accès *à* internet.

Table of contents

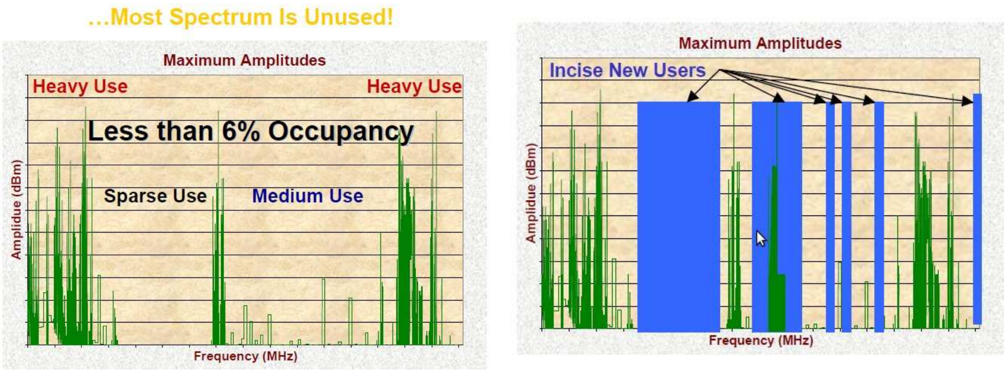
Chapter 1

Introduction

Contents

Recent advances in communication technologies and the proliferation of wireless computing and communication devices make the radio spectrum overcrowded. In this perspective, a lot of work has been carried out to improve the spectrum utilization over the last several decades. This includes the use of different access technologies, e.g., Frequency Division Multiplexing, (FDM), Time Division Multiplexing (TDM), Code Division Multiple Access (CDMA), and Orthogonal Frequency Division Multiple Access (OFDMA). From the network configuration point of view, the radio spectrum is geographically used to overcome the spectrum scarcity. For instance, in Global System for Mobile Communications (GSM), the radio spectrum is geographically re-utilized through micro, pico, and femto cells. However, experiments from the Federal Communication Commission (FCC) reveals that the spectrum utilization still varies from 15%-85% with frequency, time and geographical location (e.g., Fig. 1.1 taken from [1], [2]). Requiring, thus the need of using the radio spectrum opportunistically through Cognitive Radio (CR) technology.

Cognitive radio technology has opened new doors to emerging applications. This technology has been widely used in several application scenarios including military and mission-critical networks [3], [4], consumer-based applications [5], [6], [7], smart grid networks, public safety networks, post-disaster situations [8], [9], and wireless medical networks [10], [11], [12]. In emergency situations, with the help of multi-interface or Software Defined Radio (SDR), this technology can serve as a facilitator of communications for other devices which may operate in different band and/or have incompatible wireless interfaces. Similarly, this technology can also be used to provide opportunistic access to large parts of the underutilized spectrum in cellular networks [13].



(a) (b)

Figure 1.1: Spectrum is wasted. Opportunistic spectrum access can provide improvements in spectrum utilization (Figure taken from [1], [2]).

Cognitive radio technology can help Delay Tolerant Networks (DTNs) to provide reliable, delay-sensitive opportunities for communication [14]. For instance, DTNs and CR technology could be used in urban scenario, where high density of wireless devices causes delay in communication due to contention over the link. Cognitive radios thus help in finding empty channels for opportunistic use and ensure timely delivery of messages.

Wireless Sensor Networks (WSNs) is another domain where cognitive radio technology could be used by either providing Internet connectivity to the sink or help connecting the disjoint parts of the networks. Moreover, the cognitive radio technology can mitigate the problems of contention, collisions, and packet losses to some extent over the extremely overcrowded ISM band. This could be achieved by providing more “communication space” to sensor devices through CR technology, and thus, improves the overall spectrum utilization.

Even the opportunistic use of multiple channels by using cognitive radio capability in wireless sensor nodes can be very useful in the case of multiple sensor networks deployed over the same region for monitoring of different events [15]. In this context, a lot of work has been done on the main design challenges, application areas, energy efficiency [16], network lifetime improvement [17], distributed channel and power allocation schemes [18], and prospective network architectures of Cognitive Radio Sensor Networks [19], [20], [21], [22].

Until now, we have been discussing some applications of cognitive radio technology. We now describe the formal definition of cognitive radio and the architecture of cognitive radio networks.

1.1 Cognitive Radio Networks

Cognitive radio networks are composed of cognitive radio devices. The seminal paper of J. Mitola [23] introduced the concept of cognitive radio. Ian F. Akyildiz et al. [1] defines cognitive radio as:

"A "Cognitive Radio" is a radio that can change its transmitter parameters based on interaction with the environment in which it operates".

The motivation behind cognitive radio was threefold: (1) availability of limited spectrum, (2) fixed spectrum assignment policy, and (3) inefficiency in spectrum usage. Therefore, cognitive radio networks are designed to opportunistically exploit the underutilized spectrum. Moreover, the regulatory bodies, such as, the Federal Communication Commission (FCC) [24] also promoted the idea of using the cognitive radio devices to address the spectrum shortage problem. In this regard, the FCC has designed an interference-free opportunistic spectrum access policy [24]. In the FCC's policy [24], it is mentioned that channels are only allowed to be used by Cognitive Radio (CR) nodes if they are *idle*, i.e., not utilized by the Primary Radio (PR) nodes [1]. Moreover, CR nodes should avoid causing harmful interference to PR nodes [25] during their communication. Note that PR nodes are the legacy users and they have higher priority to use the licensed band. Idle channels can be used by CR nodes to disseminate non-urgent and publicity messages with low cost and complexity.

1.1.1 Architecture

According to the network architecture, two basic types of networks are classified, one is the Primary Network and the second one is the Cognitive Radio Network. The primary network is any existing infrastructure which has an exclusive right to access a certain spectrum band. The examples of primary networks are TV broadcast networks and Cellular networks. Primary network is composed of primary radio nodes. Fig. 1.2 shows the architectural diagram of primary network and cognitive radio networks. This figure was taken from [1]. Cognitive radio networks can be classified as *infrastructure-based* and *infrastructure-less*. Infrastructure-less CR networks can also be called as Cognitive Radio Ad-Hoc Network

(CRNs) [26].

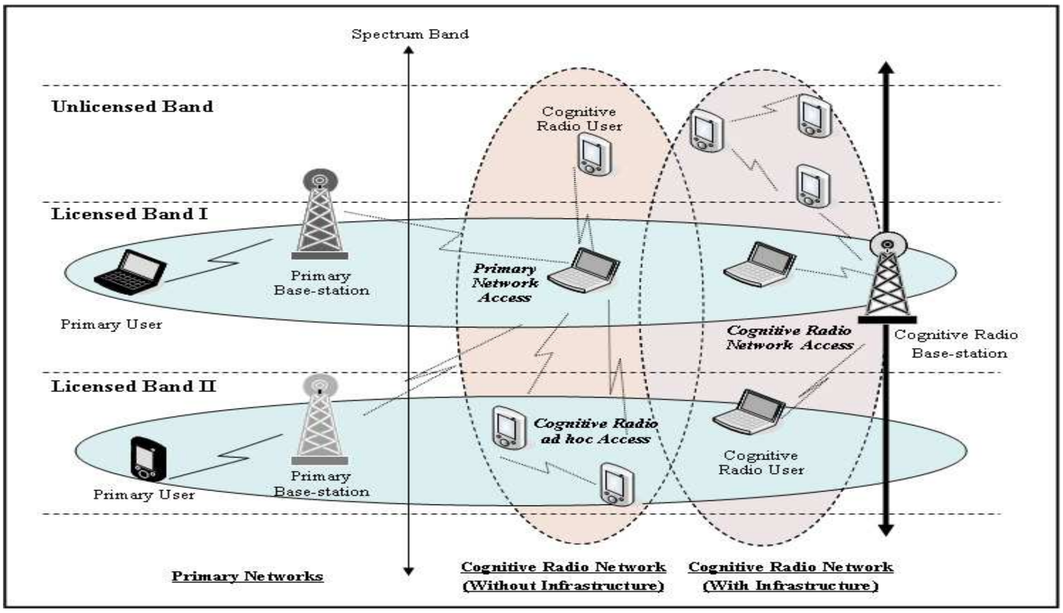


Figure 1.2: Cognitive radio network architecture (Figure taken from [1]).

The infrastructure-based cognitive radio network has a central network entity, such as an access point in wireless local area networks (LANs) or a base station in cellular networks. On the opposite, in infrastructure-less cognitive radio networks, no central entity is present.

In cognitive radio networks, according to the network architecture, different entities are responsible for the management of idle channels [2]. For instance, in infrastructure-based architectures, a spectrum broker is responsible for spectrum sensing, assignment and management, while in infrastructure-less architectures, CR nodes themselves are responsible for spectrum sensing, assignment and management. The former requires a dedicated control channel and may be exposed to different threats like Denial of Service (DoS) attack. While in the infrastructure-less architectures, the use of dedicated control channel is optional. *In this thesis, we focus on infrastructure-less architecture or Cognitive Radio Ad-Hoc Networks.*

During spectrum sensing, CR nodes detect the unused spectrum and the presence of primary radio nodes. In spectrum management, CR nodes select the best available channel. CR nodes can coordinate access to this best channel with other CR nodes during the spectrum sharing. During the spectrum mobility, CR nodes maintain seamless communication requirements and vacate the channel when a licensed node is detected on the channel.

1.1.2 Open Issues

Cognitive radio networks are an emerging research domain and there are many open issues that are still open. We highlight some of these issues here. One open issue is related to routes in CRNs, which are unstable because of the primary radio activity. As a result, the end-to-end paths are difficult to maintain. Moreover, in CR networks, channels may be of different bandwidth, and may be available for unequal time. Thus, new routing protocols are required that consider the spectrum sensing decision and primary radio activity during routing [26].

The design of Common Control Channel (CCC) is also an area where significant improvements could be done. For instance, the choice of spectrum for CCC is still an open issue. Several challenges related with MAC protocols for CRNs are discussed in [27]. For instance, the MAC protocol should cause less interference to primary radio nodes during medium access. Moreover, the MAC protocol should make efficient spectrum sensing and assignment decisions.

Connectivity is another open issue in cognitive radio enabled networks, such as disaster response networks. In post-disaster situations, devices may operate in different band and/or have incompatible wireless interfaces. Thus, CR nodes have to tune their frequency and modulation schemes, such that they are able to communicate with devices operating over different standards.

1.1.3 CRNs Standards

Recent advancements in the research of cognitive radio technology bring both the standardization organizations (IEEE, FCC, and Ofcom) and industry stake holders to create standards for CRNs. In this context, the commercialization of CR networks is no longer a dream. For example, the IEEE has two main standards [28], mainly IEEE 802.22 and SCC41 (formerly known as P1900). The IEEE 802.22 Working Group (WG) on Wireless Regional Area Networks (WRANs) is the first complete cognitive radio based international standard. Besides IEEE 802.22 and SCC41, there are several other IEEE 802 activities that are somehow related with CR standards.

Apart from these standards, several cognitive radio platforms are currently available including WARP [29], DARPA WNaN, USRP/USRP2 GNU radio [30], WiNC2R software radio [31], and KU radio. These cognitive radio hardware platforms are flexible and support high performance cognitive radio capabilities like different modulation schemes, MAC and PHY functionalities. Commercially, cognitive radios are now available in the market, e.g., FlexRadio [32].

Some testbeds that support partial cognitive radio functionalities are also available for research purpose. ORBIT Testbed [33] is one such example, which provides 400 programmable radio nodes. However, upgrading of the testbed with GNU/URSP2 radios to support programmability at the radio PHY and MAC layers is currently in progress.

1.2 Problem Statement

In this thesis, we focus on data dissemination in cognitive radio ad-hoc networks. Data dissemination is commonly defined as the spreading of information to multiple destinations through broadcasting. The main objective is to reach the maximum number of neighbors with every sent packet. In this communication scheme, no routing is required thus neither routing tables nor end-to-end paths are maintained. Among different applications where data dissemination can be useful, we focus in this work on networking scenarios where providers disseminate non-urgent messages in order to limit cost and complexity through the network, such as: services, updates (e.g., new code to re-task a provided service), or any kind of publicity message. However, guaranteeing reliability of data dissemination in wireless networks is a challenging task. Indeed, the characteristics and problems intrinsic to the wireless links add several issues in the shape of message losses, collisions, and broadcast storm problem, just to name a few.

Particularly in the context of Cognitive Radio Wireless Networks (CRN) [1], where channels for transmission are opportunistically selected, reliability is difficult to achieve. This is due to the inherent features of such networks. First, in addition to the already known issues of wireless environments, the diversity in the number of channels that each cognitive node can use adds another challenge by limiting node's accessibility to its neighbors. Second, cognitive radio nodes have to compete with the primary radio nodes for the residual resources on channels and use them opportunistically. Besides, CR nodes should communicate in a way that does not disturb the reception quality of PR nodes by limiting CR-to-PR interference [25].

In *infrastructureless multi-hop cognitive radio ad-hoc networks*, where coordination between CRs is hard to achieve and no central entity for regulating the access over channels is present, robust data dissemination is even more complex. In this perspective, the important step in having efficient data dissemination is to know *how to select best channels*. In fact, channel selection plays a vital role in robust data dissemination. If CR nodes select the channels randomly, there are very less chances that the neighbor receivers also select the same channel for overhearing. Consequently, the random selection of channels severely degrades the data dissemination reachability. Furthermore, when CR nodes randomly select the channel for transmission, it may be possible that a PR transmission is going-on on that channel, resulting in the generation of harmful interference to the PR nodes. Therefore, a new channel selection strategy is required that works well with single transceiver, cause less harmful interference to PR nodes, and try to maximize the chances that the message is delivered to the neighboring cognitive radio receivers, thus increasing the data dissemination reachability.

1.3 Contributions of the thesis

At the following, we first describe our contributions in this thesis, then we describe the methodology adopted in this thesis.

1.3.1 Proposed Solutions

The first contribution of this thesis is a channel selection strategy, named SURF [34–36], for data dissemination in multi-hop cognitive radio ad-hoc networks. In SURF, the classification of channels is done on the basis of primary radio unoccupancy and the number of cognitive radio neighbors using the channels. SURF makes efficient and reliable channel selection decisions on-the-fly and recovers from bad channel selection decisions. SURF keeps track of previous wrong channel state prediction and accordingly adapts future channel selection decision. Usually channel selection strategies provide a way to nodes to select channels for transmission. On the contrary, SURF endues CR nodes to select best channels not only for transmission but also for overhearing. This will help to tune both sender and receiver with high probability to the same channel. As a consequence, SURF may have high number of neighbors on the selected channel. In addition to that, SURF protects the PR nodes by considering the PR unoccupancy in channel selection decision, for effective and robust data dissemination.

The second contribution of thesis is the enhancement of Network Simulator NS-2 to include the PR activity model. In fact, Network Simulator NS-2 has been widely used in the wireless networking research. We also opted for NS-2 in our simulation-based studies. Nevertheless, due to the fact that research in CRNs is very recent, a complete and accurate simulation module for CRNs in NS-2 was not yet available. In order to deal with such lack, we modified the NS-2 and added missed CRNs functionalities. We used the Cognitive Radio Cognitive Network (CRCN) patch of NS-2. This CRCN patch of NS-2 does not support the activity of the PR nodes. Thus, we enhance the CRCN patch of NS-2 to include the PR activity model. Moreover, we also modified the MAC protocol to incorporate the PR activity model in NS-2. More details can be found in section 3.5 and appendix B.

We observe that the channel selection strategies are greatly influenced by the primary radio nodes activity. We study the impact of primary radio nodes activity on four channel selection strategies, which is the third contribution of this thesis [37].

The fourth and the final contribution of this thesis is the applicability of SURF. In this perspective, we propose a cognitive radio based Internet access framework for disaster response networks [38]. We discuss the architectural details of the proposed framework. Further, we discuss the working principle of the framework. We highlight the challenges and issues related with the deployment and connectivity of the framework. Finally, we discuss the applicability of SURF in the context of channel bonding and in this regard, we discuss an interference based channel bonding strategy for cognitive radio networks.

1.3.2 Methodology

We have designed SURF and selected the realistic PR activity model for our analysis. Initially, we tested some basic properties of SURF in home-made simulator, implemented in C++. Note that these results are not mentioned in this thesis. The home-made simulator does not provide real propagation and link-access conditions, required for a more realistic simulation environment to evaluate SURF. Thus, we opted to use Network Simulator NS-2 to perform the simulations and analyze SURF. However, there was only one patch available that supports some partial features of cognitive radio networks. Thus, we enhanced NS-2, and included the ON/OFF PR activity model. We also modified the mac protocol and implemented the ON/OFF activity. We then performed extensive simulations in both single-hop and multi-hop scenarios, analyze the performance of SURF, and compared it with three other related approaches.

Simulations results revealed that the performance of cognitive radio networks is highly dependent upon the primary radio nodes activity pattern. Therefore, we broaden our scope and study and analyze different PR nodes activity. The performance of four channel selection strategies under different PR nodes activity pattern through extensive NS-2 simulations is then discussed. Moreover, we also analyze how these strategies respond to different PR nodes activity.

In this thesis, we have also considered the practical scenarios where SURF could be implemented. SURF is simplistic in nature, thus, the post-disaster situations are more feasible for the deployment of SURF. For post-disaster situations, we propose an Internet access framework for disaster response network deployments in challenged environments. In addition, we discuss the feasibility and applicability of SURF in the context of channel bonding by discussing C-BOND, interference based channel bonding strategy.

1.4 Outline of Thesis

This thesis document is structured into six chapters. Following this chapter, in chapter 2, we provide the challenges of data dissemination and classification of channel selection strategies in cognitive radio networks. In chapter 3, we discuss our channel selection strategy SURF. In addition, we also discuss the modifications of NS-2 in the same chapter. We discuss the impact of primary radio nodes activity on channel selection strategies, such as RD, HD, SB, and SURF, in chapter 4. We discuss the applicability and feasibility of SURF in chapter 5. We conclude this thesis and give possible directions for future research in chapter 6.

We provide all the thesis publications in appendix A. In appendix B, we provide NS-2 contributed code and the modifications that we have done to include the PR activity model. Thesis that is written in English language must provide a summary in French language, which is the requirement, imposed by Université Pierre et Marie Curie (UPMC) – Sorbonne Universités. Thus, a summary in French language of this thesis can be found in appendix C.

Chapter 2

Data Dissemination and Channel Selection in Cognitive Radio Networks

Contents

Data dissemination is a classical and a fundamental function in any kind of network. Data Dissemination corresponds to the spreading of information through broadcasting. The main objective is to reach the maximum number of neighbors with every sent packet i.e., no explicit routing is used and no end-to-end path is maintained. Data Dissemination has been studied in different wireless networks, such as Wireless Sensor Networks (WSNs), Vehicular Ad-Hoc Networks (VANETs), Wireless Mesh Networks (WMNs), and Mobile Ad-Hoc Networks (MANETs).

In wireless networks, the characteristics and problems intrinsic to the wireless links bring several challenges in data dissemination (broadcasting) in the shape of message losses, collisions, and broadcast storm problem, just to name a few. If broadcasting is done through flooding, i.e., blindly, serious redundancy, contention, and collision could exist [39]. First, many broadcasts are considered to be redundant because the radio propagation is omnidirectional and a geographical location may be covered by the transmission ranges of several hosts. Second, after a node broadcast a message, if many of its neighbors decide to rebroadcast, these transmissions may severely contend with each other. Third, the timing of rebroadcast of the neighboring nodes may cause collisions. All these three problems associated with flooding, collectively referred as broadcast storm problem. One method to reduce the broadcast storm problem is to inhibit some wireless nodes from rebroadcasting, which results in less contention and collision. It has been proved that if a simple counter-based scheme is used instead of simple flooding, it can eliminate many redundant rebroadcasts [39]. One such method is probabilistic broadcasting, where wireless nodes rebroadcast with certain probability.

In cognitive radio networks, broadcasting is expected to be done more frequently due to the higher spatio-temporal availability of channels. The situation is more complex than multi-channel wireless networks, where the availability of multiple channels are static. On the contrary, channels are dynamic in cognitive radio networks due to the primary radio activity. Therefore, the broadcast storm problem is present in cognitive radio networks. In cognitive radio networks, an important step in having efficient data dissemination is to know how to select best channels. In fact, channel selection plays a vital role in robust data dissemination.

The goal of this chapter is to provide a comprehensive review of broadcasting and channel selection strategies, for both wireless and cognitive radio networks. The methodology we adopt in this chapter is to first discuss some applications of data dissemination in wireless networks in section 2.1. We then provide the classification of broadcasting protocols in section 2.2. Data dissemination in multi-channel environments is discussed in section 2.3. Challenges of data dissemination in cognitive radio networks are discussed in section 2.4, followed by the classification of channel selection strategies in section 2.5. Finally, in section 2.6, we conclude this chapter.

2.1 Applications of Data Dissemination in Wireless Networks

In vehicular ad-hoc networks, an interesting application is to disseminate emergency messages to the specific area while guaranteeing all relevant vehicles receive the emergency message, such that people can change their routes to destination in time. In this way, people can avoid getting into a traffic jam. In this context, an analysis of emergency message dissemination in vehicular networks is done in [40]. In [41], a fast and reliable emergency message dissemination mechanism was proposed to disseminate emergency message in VANETs. In addition, the authors discussed how to solve the broadcast storm problem, achieving low dissemination delay, and providing a high reliability in freeway scenario [41].

Data dissemination in wireless sensor networks has been widely studied in the literature. In WSNs, data dissemination is generally performed from sensor nodes to a static sink. This data could be an emergency message such as a fire alarm, and it must be transmitted fastly and reliably towards the sink. Note that in emergency situations, the sink could move, e.g., a fire fighter roaming in the area or an Unattended Aerial Vehicle (UAV). For e.g., the authors in [42] proposed data dissemination protocol for emergency message transmission in mobile multi-sink WSNs. In [43], the authors proposed density-based proactive data dissemination protocol, Deep, for wireless sensor networks with uncontrolled sink mobility. Similarly, a proactive data dissemination approach, called Supple, for data gathering in self-organized Wireless Sensor Networks is proposed in [44]. Supple effectively distributes and stores monitored data in WSNs such that it can be later sent to or retrieved by a sink.

Epidemic dissemination has huge potential, enabling, for instance, a wide range of mobile ad-hoc communication and social networking applications, supported entirely through opportunistic contacts in the physical world. For instance, the authors in [45] improved the understanding of data dissemination in opportunistic mobile ad hoc networks. In fact, their work is a first step in studying the impact of social behaviour of users on information dissemination. Another application where epidemic dissemination could be used is WSNs. Directed diffusion [46] is one such example, where interest propagation is done through flooding. At the following, we discuss the classification of broadcasting protocols.

2.2 Classification of Broadcasting Protocols

Broadcasting protocols in wireless networks can be classified into two major categories: (1) stateful broadcasting protocols, and (2) stateless broadcasting protocols. Stateful broadcasting algorithms require the nodes the knowledge of network topology in their local neighborhood and this is commonly achieved by proactive exchange of hello messages between neighbors. On the opposite, stateless broadcasting protocols do not require any knowledge of the neighborhood. Stateless broadcasting protocols were shown to perform well in specific scenarios but very poorly in others, e.g. for varying node density and traffic loads. A very detailed discussion on the taxonomy of broadcasting protocols for wireless mobile ad-hoc networks can be found in [47]. Fig. 2.1 shows the classification of broadcasting protocols, as briefly described in the following:

- Stateful Broadcasting Protocols: Stateful broadcasting protocols can be classified according to how the neighbor is designated.

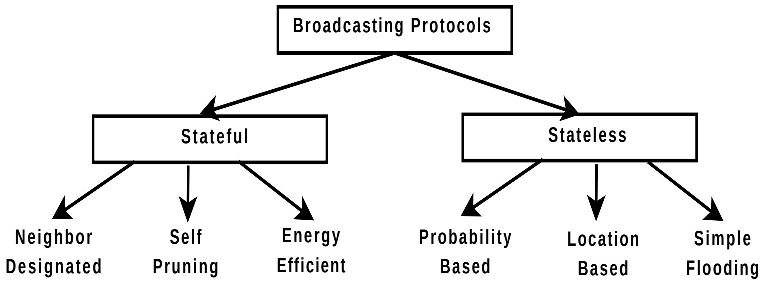


Figure 2.1: Broadcasting protocols and their classification.

  - Neighbor Designated: In neighbor designated broadcasting protocols [48], a node that transmits a packet specifies which one of its one-hop neighbors should broadcast the packet.
  - Self Pruning: In self pruning broadcasting protocols [49], a node receiving a packet will decide itself whether or not to transmit the packet.
  - Energy Efficient: Energy efficient broadcasting protocols [50] are those protocols that consider the energy consumption during broadcasting.

- Stateless Broadcasting Protocols: Stateless broadcasting protocols can be classified as follows:
  - Probability Based: In probability-based broadcasting protocols [39, 51, 52], each node broadcasts with a certain probability p and drops the packet with a probability of $1 - p$.
  - Simple Flooding: Simple flooding is the broadcasting scheme in which each node broadcast a packet with probability 1.
  - Location Based: Location-based broadcasting protocols [39] are those protocols in which a node rebroadcasts a packet on the distance between itself and the node from which that packet is received.

Note that all the aforementioned broadcasting schemes cannot be directly applied to cognitive radio networks. Primarily due to the challenges specific to cognitive radio networks, as classified in section 2.4.

2.3 Data Dissemination in Multi-Channel Environment

In this section, our goal is to briefly discuss some data dissemination protocols for multi-channel environment.

In [53], the authors proposed two protocols, McSynch and McTorrent, for data dissemination in multi-channel wireless sensor networks. McTorrent achieves end-to-end data dissemination in less time than the single channel protocols, while McSynch can substantially reduce the time required for a cluster-wide synchronization. In [54], the authors analyzed the performance limits of data dissemination with multi-channel, single radio sensors under random packet loss. The authors showed that, for an arbitrary topology, the problem of minimizing the expected delay of data dissemination can be treated as a stochastic shortest path problem. Broadcasting on multiple access channels by deterministic distributed protocols are studied by authors in [55]. The authors compared the packet latency of deterministic protocols and backoff-type randomized protocols.

Broadcasting protocols for multi-channel wireless networks in the presence of adversary attacks are proposed in [56]. The authors used network coding for data dissemination in order to reduce the impact of suck adversary attacks on dissemination performance and derived the optimum number of channels that nodes have to access in order to minimize the reception delay. A power saving data dissemination architecture for mobile clients' units in multi-channel environment is proposed in [57]. The authors proposed a concurrency control technique suitable for the multi-channel dissemination-based architectural model. A data scheduling algorithm over multiple channels in mobile computing environment is proposed in [58]. The authors formulated the average expected delay of multiple channels considering data items' access frequencies, variable length, and different bandwidth of each channel.

In cognitive radio networks, very less work has been done on data dissemination. For e.g., in [59], the authors investigated the distribution and limits of information dissemination latency and speed in cognitive radio networks. Hereafter, we discuss the challenges of data dissemination in cognitive radio networks.

2.4 Challenges of Data Dissemination in Cognitive Radio Networks

Robust data dissemination is a challenge in cognitive radio networks due to its intrinsic properties, such as:

- the availability of multiple-channels i.e., CR nodes have more than one channel in the available channel set. Available channel set is the set of channels eligible by CR nodes for any communication.

- the diversity in the number of available channels i.e., CR nodes have diverse set of available channels in the available channel set.
- the primary radio activity i.e., channels are occupied by the PR nodes and are only available to CR nodes for transmission when they are *idle*. In fact, the spatiotemporal utilization of spectrum by PR nodes (i.e. primary radio nodes' activity) adds another challenge to data dissemination. As a consequence, the number of available channels to CR nodes changes with time and location leading to the diversity in the number of available channel set. Because of PR's activity, the usability of the channels by CR nodes becomes uncertain.

Moreover, without any centralized entity, as in the case of multi-hop ad hoc cognitive radio network, data dissemination is even more challenging because CR nodes have to rely on locally inferred information for their channel selection decision. If a channel selection is done in an intelligent way, higher data dissemination reachability can be achieved. Furthermore, the consideration of PR activity during channel selection can enhance the effectiveness of data dissemination reachability and can reduce the harmful interference to PR nodes by CR transmissions.

Considering the previous described observations, hereafter we describe the key characteristics required by a channel selection strategy for improving data dissemination robustness in infrastructureless multi-hop cognitive radio ad-hoc networks:

1. CR neighbor reception: A good channel selection strategy is the one that increases the probability of higher message delivery to the CR neighbors in multi-hop context.
2. Primary radio constraints: The channel selection strategy should ensure that the transmission on the selected channel does not create harmful interference to primary radio nodes.
3. Autonomous decision by CR nodes: In decentralized infrastructureless multihop cognitive radio networks, CR nodes are required to take autonomous decisions. It means that the channel selection strategy should work well without any centralized authority and channel selection decision should be based on locally inferred information.
4. Sender/Receiver tuning: The channel selection strategy should guarantee that the CR transmitter and receiver select the same channel with high probability.

In the following section, we provide a classification of channel selection strategies in cognitive radio networks.

2.5 Classification of Channel Selection Strategies in CRNs

Recently, a lot of channel selection strategies have been proposed for cognitive radio networks [60–70]. These channel selection strategies are designed to achieve different performance goals, for instance, optimization of throughput, delay, etc. Besides achieving these goals, each channel selection strategy has a nature, according to its reaction with the appearance of PR nodes on the CR communicating channel. Therefore, channel selection strategies can be classified into three categories by nature: (1) proactive (predictive), (2) threshold based, and (3) reactive. From the algorithmic perspective, channel selection strategies can be classified into centralized and distributed. The classification of channel selection strategies in cognitive radio networks is shown in Fig. 2.2. Table 2.1 compares different channel selection strategies for cognitive radio networks and their features. In the following, we discuss each classification in detail.

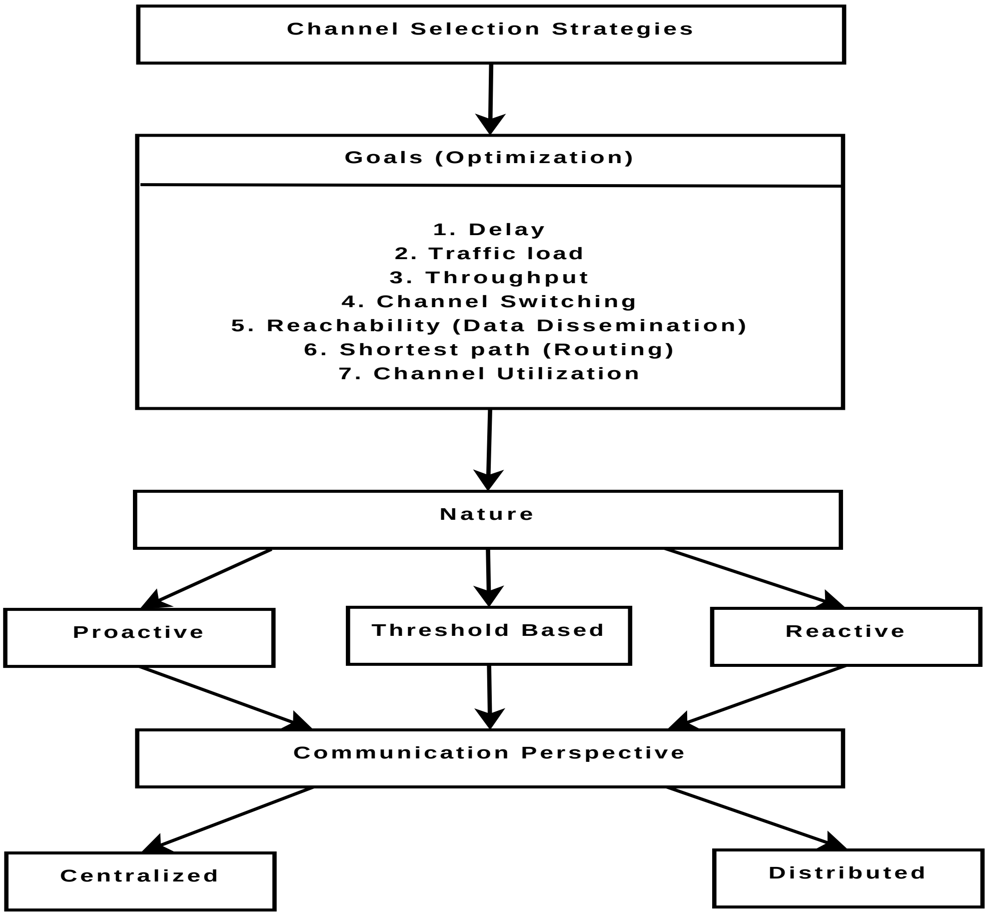


Figure 2.2: Classification of channel selection strategies for Cognitive Radio Networks.

2.5.1 Goals of Channel Selection Strategies

Channel selection strategies have been used to achieve different goals, e.g., load balancing, throughput maximization, channel switching delay minimization etc. Authors in [60] proposed a channel selection strategy to satisfy the traffic demands of Access Points. Throughput maximization is another goal and several channel selection strategies were proposed for throughput maximization [63, 68, 70, 72, 73]. In [68], the authors determined the transmission schedule of the CR nodes in order to improve the network throughput. In [70], the authors improved the throughput of the CR users in the TV broadcast network. In fact, the authors proposed a predictive channel selection scheme to maximize spectrum utilization and minimize disruptions to PR nodes. They considered a single-hop network in which CR nodes coordinate with the TV receiver to collect information regarding PR activity. Two opportunistic channel selection schemes, CSS-MCRA and CSS-MHRA, are proposed in [72]. In CSS-MCRA, the goal was to maximize the throughput while minimize the collision rate. In CSS-MHRA, the goal was to maximize the throughput while minimizing the handoff rate. CSS-MCRA and CSS-MHRA both considered single user and are predictive in nature.

Load balancing is another important goal of channel selection strategies [74, 75]. In [74], the authors proposed a channel and power allocation scheme for CR networks. The objective was to maximize the sum data rate of all CRs. They considered the availability of a centralized authority, which monitors the PR activity and assign channels to CR nodes. Sensing-based and probability-based spectrum decision schemes are proposed in [75] to distribute the load of CR nodes to multiple channels. The authors derived the optimal number of candidate channels for sensing-based scheme and the optimal channel selection probability for probability-based spectrum decision scheme. The objective of both schemes was to minimize the overall system time of the CR users.

The authors in [76] proposed a predictive channel selection scheme to minimize the channel switching delay of a single CR node. Other channel selection strategies focus on optimizing the expected waiting time [77, 78], remaining idle time [71, 79], reducing system overhead and improving CR QoS [80]. A predictive channel selection strategy, Voluntary Spectrum Handoff (VSH) [71], is proposed to reduce the communication disruption duration due to handoffs and to select the channel that has maximum remaining idle time. However, VSH requires the presence of Spectrum Server (SS), a centralized entity, to monitor the activities of PR and CR nodes. In [66], the authors proposed a channel selection scheme to maximize the total channel utilization. In their paper, the authors consider source-destination pairs in single-hop context. Channel selection strategies can also be used in conjunction with routing protocols for reliable path selection [25] and good route selection for delay sensitive applications [81].

Table 2.1: Channel selection strategies and their features.

Strategy	**Goal**	**Nature**	**Hop/User**
VSH [71]	Remaining idle time	Predictive	Centralized
[70]	Maximize channel utilization, throughput maximization and minimize disruptions to PRs	Predictive	Single-hop
SWIFT [65]	Combine multiple non-contiguous unoccupied bands to create a high-throughput wideband link	work on unlicensed band	N/A
CBH, LH [67]	Maximize channel utilization & decrease message overhead	Reactive	Multi-hop
WAIT [69]	Maximize throughput	Reactive	Single-hop
CSS-MCRA [72]	Minimize collision rate and Throughput maximization	Predictive	Single user
CSS-MHRA [72]	Minimize handoff rate and Throughput maximization	Predictive	Single user
[68]	Throughput maximization	Threshold based	Centralized
PS-OSA [73]	Throughput maximization	N/A	CR pairs
[74]	Load balancing	Reactive	Centralized
[75]	Load balancing	Predictive/Reactive	Single-hop
[76]	Reduce channel switching delay	Predictive	Single user
SCA-MAC [77]	Expected waiting time	Predictive	N/A
POSH [78]	Expected waiting time	Predictive	N/A
FLEX [60]	Traffic demands of Access Points	N/A	Single-hop
IEEE 802.22 [61]	International wireless standard based on CR technology to use TV spectrum without causing harmful interference to TV devices	N/A	Centralized
[79]	Remaining idle time	Proactive	CR pairs
[80]	Reduce system overhead and improve CR QoS	N/A	N/A
[66]	Maximize total channel utilization	Reactive	CR pairs
MPP [25]	Reliable path selection	N/A	Multi-hop
[81]	Route selection for delay sensitive applications	Reactive	Distributed
[82]	Route selection for delay sensitive applications	Reactive	Distributed
[62]	Find longest idle time channel	Predictive	N/A
[83]	Optimize delay in finding the channel	Proactive	N/A
PRO-I, PRO-II [84]	Minimize disruptions to PRs, throughput maximization	Proactive	Single pair
[85]	Reduce delay & channel switching, maximize throughput	Predictive	N/A
PDSA [86]	To determine expected channel idle time	Predictive	N/A
[87]	Outage requirement of PR user CR	Reactive	Centralized
RMC-MAC [88]	Reduce forced termination probability and increase bandwidth utilization	Reactive	Single-hop
DFHC [89]	Better QoS and maximize throughput	Reactive	Centralized
SB [90]	Data Reachability	N/A	Distributed
SURF (cf. Chapter 3)	Data Reachability, minimize disruptions to PRs	Predictive	Distributed

2.5.2 Nature of Channel Selection Strategies

According to the reaction with the appearance of PR nodes on the CR communicating channel, every channel selection strategy has a nature. Therefore, by nature, channel selection strategies in cognitive radio networks can be classified into proactive (predictive), threshold based, and reactive.

- Proactive Channel Selection Strategies: In proactive channel selection strategies [62, 70, 76, 83–86], the activity of PR nodes is predicted and the CR nodes move to the channel according to the prediction. In [85], the authors proposed a predictive channel selection strategy to reduce delay and channel switching, while maximizing the throughput. The same authors further extend their work in [62] and classified the PR traffic and applied different prediction rules. These prediction rules were then used in the predictive channel selection scheme to find the channels with the longest idle times for CR use.

  In [86], the authors explored two approaches of predictive dynamic spectrum access (PDSA). The first approach uses cyclostationary detection on the primary users' channel access pattern to determine expected channel idle times. The second approach briefly examines the use of Hidden Markov Models (HMMs) for use in PDSA. Their basic goal was to predict when the channels will be idle, based on observations of the primary radio nodes channel usage. They determined the expected channel idle times for CR usage. Two proactive channel selection strategies, PRO-I and PRO-II are proposed in [84]. The goals of these schemes was to minimize disruptions of PR nodes and throughput maximization of CR nodes. The authors used a single pair of CR nodes and they ignored the impact of other CR nodes contending for the channel.

  The authors in [83] proposed a proactive channel selection scheme. Through their scheme, the authors tried to optimize the delay in finding the channels using the history. Their scheme is based on two steps: the database step and the signal detection step. In the database step, the database collects information about the channels. The CR node, when required a channel for transmission, sends a query to the database. The database then provides the most probable unoccupied channels, which are the best candidates for searching the channels. These channels are then submitted to the CR node. CR node then selects the channels according to the priority which is based on the signal detection history.

- Threshold-Based Channel Selection Strategies: The threshold based schemes are those channel selection schemes in which the PR node is active all the time i.e., occupy the channel 100% and no *idle* channel is available to CR nodes. In these schemes, CR nodes are allowed to share the channel as long as the interference caused by the CR nodes to the PR nodes is below a certain threshold. Threshold-based schemes are also known as schemes that uses grey spaces. For instance, [68] is a threshold based channel selection scheme, in which the authors determined the transmission schedule for the CR nodes to maximize their throughput.

- Reactive Channel Selection Strategies: In reactive channel selection strategies [87, 88, 91–93], channel switching occurs after the PR node appears. In fact, in reactive channel selection schemes, CR nodes monitor local spectrum through individual or collaborative sensing. A lot of work has been done on individual or collaborative sensing, which can be found here [91–96]. After detecting a change in the spectrum, e.g., channel is occupied by PR node, CR nodes stop the transmission, return back the channel to the PR node and search for other channel to resume the transmission. In [97], the co-authors of [98] provided the modeling and analysis of reactive spectrum handoff scheme in more detail.

  In [87], the authors proposed a sensing-based opportunistic channel access scheme. They considered a Primary TV broadcast network. They also considered a single PR node and a single CR node and a base station is required for keeping the primary channel's statistics. A reactive multi-channel mac protocol, RMC-MAC, for opportunistic spectrum access is proposed in [88]. Their objective was to increase the bandwidth utilization and to reduce the forced termination probability. However, they considered a single-hop CR network. Dynamic frequency hopping communities (DFHC) [89] is also a reactive approach, which is designed for IEEE 802.22 networks and requires the presence of base station.

In [98], the authors compared two types of spectrum handoff schemes: proactive (predictive) and reactive spectrum handoff schemes. In reactive-sensing handoff scheme, the target channel is selected after the spectrum handoff request is made. While in proactive spectrum handoff scheme, the target channel is predetermined. The authors mentioned that the advantage of reactive spectrum handoff scheme resides in the accuracy of the selected target channel, but incurs the cost of sensing time. On the contrary, the proactive spectrum handoff scheme avoids the sensing time, but the pre-determined channel may not be available.

2.5.3 Channel Selection Strategies from the Communication Perspective

From the communication perspective, channel selection strategies can be classified into centralized and distributed. In [99], a comparison between centralized and distributed approaches for spectrum management is provided.

- Centralized Channel Selection Strategies: In centralized channel selection strategies, a centralized entity is present, which helps CR nodes in their channel selection decision, e.g., [100–102]. The authors in [103] investigated different steps for the development of centralized algorithms for different radio networks. They discussed the current interests of regulators, technical requirements, and the possible schemes for dynamic spectrum allocation. In [60], the authors proposed an efficient spectrum allocation architecture that adapts to dynamic traffic demands but they considered a single-hop scenario of Access Points (APs) in Wi-Fi networks. An approach that uses non-continuous unoccupied band to create a high throughput link is discussed in [65]. In [68], the authors proposed a threshold-based channel sharing scheme between CR nodes. Their algorithm is designed for source-destination pairs and is specially designed for single-hop communication. In their paper, the authors assumed that all the PRs are active all the time and no *idle* channel is available to CR nodes for their communication. A centralized channel allocation scheme for IEEE 802.22 standard is proposed in [104]. The proposed channel allocation scheme allocates the channel based upon three rules: (1) maximum throughput rule, (2) utility fairness rule, and (3) time fairness rule. The authors in [105] proposed an opportunistic channel selection scheme for IEEE 802.11-based wireless mesh networks. In this channel selection scheme, an Access Point (AP) is required to connect the nodes to the Internet via mesh router.

- Distributed Channel Selection Strategies: In distributed channel selection strategies, there is no centralized entity that helps CR nodes in their channel selection decision. CR nodes need to take channel selection decision on their locally available information. Very few works has been done on distributed channel selection strategies in the context of cognitive radio networks [81, 82, 90]. In [81, 82], the authors proposed a dynamic resource management scheme for multi-hop cognitive radio networks, in which routes are maintained for delay sensitive applications, such a multimedia streaming. The authors studied the amount of information exchange required in the multi-hop network. Based on the available information exchange, the authors proposed a multi-agent learning approach which allows the various nodes to optimize their transmission strategies autonomously, in a distributed manner, in multi-hop cognitive radio networks. In addition, the channel selection scheme proposed in [81, 82] is designed to work with routing protocols, and thus cannot be used for broadcasting.

  Selective broadcasting (SB) [90] is a distributed channel selection strategy. In SB, each cognitive node selects a minimum set of channels (ECS) covering all of its geographic neighbors to disseminate messages in multi-hop cognitive radio networks.

There are however, several challenges in the practicality of SB. Indeed, from the communication perspective, simultaneous transmission over a ECS requires more than one transceiver, which means having bigger and more complex devices, as it is done for military applications [4]. On the contrary, using a single transceiver to transmit over minimum set of channels requires determining the correct channel to overhearing a transmission, increases delay, and brings frequent channel switching. Secondly, from the perspective of overhearing, either neighbor nodes need to simultaneously overhear over multiple channels or synchronization is required among neighbors, which incurs scheduling overhead.

2.6 Conclusion

Data dissemination has been widely studied in several wireless networks including wireless sensor networks, vehicular ad-hoc networks, and mobile ad-hoc networks. In this chapter, we gave an introduction on data dissemination in these types of networks. We then discussed the related works and the challenges associated with data dissemination in cognitive radio networks. Additionally, we highlighted that channel selection plays a vital role in efficient and robust data dissemination. We provided an in-depth study of channel selection strategies in cognitive radio networks. Furthermore, classification of channel selection strategies according to their goals, nature, and communication perspective were provided.

In the following chapter, we will describe our channel selection strategy SURF for data dissemination in multi-hop cognitive radio networks.

Chapter 3

SURF: Channel Selection Strategy for Data Dissemination

Contents

In the previous chapter, we have described comprehensively the state-of-the-art on data dissemination and channel selection strategies for wireless networks. In the context of data dissemination in infrastructureless multi-hop cognitive radio networks, very less work has been done so far. The most relevant work that we found in the literature is Selective Broadcasting (SB) [90] approach. In SB, CR nodes require to transmit over minimum set of channels to cover all its geographical neighbors. However, there are several issues in the practicality of SB. First, using a single transceiver to transmit over minimum set of channels requires determining the correct channel to overhearing a transmission, increases delay, and brings frequent channel switching. Secondly, from the perspective of overhearing, either neighbor nodes need to simultaneously overhear over multiple channels or synchronization is required among neighbors, which incurs scheduling overhead.

In this chapter, we describe SURF, a distributed channel selection strategy for data dissemination in multi-hop cognitive radio networks. We analyzed SURF in detail and compared it with three relevant approaches.

The remainder of this chapter is organized as follows: we discuss system model and assumptions in Section 3.1. We give general overview of SURF in Section 3.2. Section 3.3 and 3.4 deal with detailed description of SURF. Simulation environment is described in section 3.5. SURF parameters evaluation and SURF comparison is done in section 3.6 and section 3.7, respectively. Finally, section 3.8 concludes the chapter.

3.1 System Model and Assumptions

In this section, we present the system model considered and the basic assumptions related to our proposal.

Network Model We consider a Cognitive Radio Ad-Hoc Network [26]. In this type of network setting, we assume that no centralized network entity is available. Instead, we consider a networking environment where network operations (e.g., spectrum sensing, channel selection decision etc) are performed by the CR nodes themselves. The network is composed of a set of Primary Radio (PR) nodes and a set of Cognitive Radio (CR) nodes. Primary radio nodes are the licensed users and they can access their respective licensed bands without any restriction. Indeed, PR nodes have the highest priority to access the channels and should not be interrupted by the CR nodes [25].

In order to be able to communicate in a CRN, CR nodes must create a multi-hop network by using the licensed bands. The use of licensed bands by cognitive radio nodes are however, only possible when the bands are *idle*, i.e. unoccupied by the PR nodes. However, there are some approaches [68], where CR nodes use grey spaces (in which CR nodes are allowed to share the channel as long as the interference caused by the CR nodes to the PR nodes is below a certain threshold). Note that an *idle* state describes the temporal availability of a channel. In some cases, it can happen that a CR node starts a transmission at the same time when PR becomes active. Since, we consider that CR transmissions should not generate harmful interference at PR receivers [106], CRs will cancel their transmissions.

We further assume that CR nodes are equipped with a single transceiver. This transceiver can either receive or transmit on a single channel at a time. The utilization of single transceiver reduces the operational cost of the CR devices [107], as well as avoiding potential interference between co-located transceivers due to their close proximity [108]. We consider the set of total frequency channels C. We assume the availability of a *out-of-band* Common Control Channel (CCC) [26] for neighbor discovery.

Spectrum Sensing by Cognitive Radio Nodes In cognitive radio ad-hoc networks, cognitive radio nodes are assumed to work in standalone fashion and make decisions based on locally inferred information. As a consequence, each CR node has to perform spectrum sensing to detect the presence of the PR signal. We assume that the spectrum sensing is periodically performed by every CR node. We further assume that the detection of the PR signal is the responsibility of the spectrum sensing block [109]. The spectrum sensing block perform spectrum sensing through which CR nodes obtain awareness about the spectrum usage and existence of primary radio nodes in a geographical area. Note that SURF will work on the list of available channels resulting from the spectrum sensing.

Several techniques for spectrum sensing have been proposed in the literature but they mainly fall into five categories [109]: (1) Energy Detector based sensing [110,111], (2) Waveform based sensing [112], (3) Cyclostationarity-based sensing [110], (4) Radio Identification based sensing [113], and (5) Matched-Filtering [114]. The spectrum sensing method should be selected by considering the tradeoff between the complexity and accuracy. Moreover, one of the major challenge in spectrum sensing is how to differentiate precisely between primary transmissions from CR transmissions. The two types of transmissions can be distinguished through existing spectrum sensing scheme based on energy detectors [115]. When energy detectors are used, a CR node can recognize the signals of other CR nodes but cannot recognize PR signals. When a CR detects a signal that it recognizes, it assumes that the signal is that of a CR node; otherwise it determines that the signal is that of a PR node.

Primary Radio Activity or Wireless Channel Model The performance of cognitive radio network is closely related to the primary radio activity over the channels. Therefore, the estimation of primary radio activity plays a vital role in channel selection decision. We assume that the primary radio activity on wireless channels can be modelled as a continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [116–118] (cf. Section 3.3 for more details). Note that such an ON/OFF PR activity model captures the time period in which the channel can be utilized by CRs without causing any harmful interference to PR nodes [119].

3.2 Channel Selection Strategy SURF

The SURF channel selection strategy is specifically designed for ad-hoc cognitive radio networks. The general goal of SURF is to increase the reliability in data dissemination over a multi-hop ad hoc CRN. Note that SURF is a packet-based channel selection scheme for data dissemination and not a routing algorithm. Therefore, neither the routing tables nor the end-to-end paths are maintained by the CR nodes. CR nodes, upon each packet reception, select the best channel, and broadcast the packet.

With SURF, every CR node autonomously classifies available channels based on the observed PR-unoccupancy over these channels. This classification is then refined by identifying the number of CRs over each band. The best channel for transmission is the channel that has the higher PR unoccupancy and a higher number of CR neighbors. Indeed, choosing a channel with few CRs may yields to a disconnected network. Every CR after classifying available channels, switches dynamically to the best one and broadcasts the stored message. Moreover, SURF also tries to learn with the previous wrong channel state prediction. This learning process allows a better tuning of the future predictions and helps CR nodes to recover from their bad channel selection decisions.

Additionally, CRs with no messages to transmit implement the SURF strategy in order to tune to the *best* channel for data reception. Using the same strategy implemented by the sender allows receivers in close geographic areas to select with a high probability the same used-to-send channel for overhearing. This will also increase the number of CR neighbors on the selected channel. This is due to the fact that, intuitively, it is likely that CRs in the sender's vicinity have the same PR unoccupancy, hence channels availability is common for a sender and its neighbors [63]. Therefore, SURF increases the probability of creating a connected topology. Once a packet is received, every CR receiver undergoes again the same procedure to choose the appropriate channel for conveying the message to its neighbor.

Channel's Weight Calculation Formula SURF strategy classifies channels by assigning a weight $P_w^{(i)}$ to each observed channel i in the channel set C. Thus, every cognitive radio node running SURF, locally computes the $P_w^{(i)}$ using the following equation:

$$\forall i \in C : P_w^{(i)} = PR_u^{(i)} \times CR_o^{(i)} \tag{3.1}$$

$P_w^{(i)}$ describes the weight of a channel (i) and is calculated based on the PR unoccupancy (i.e. $PR_u^{(i)}$) and CR occupancy (i.e. $CR_o^{(i)}$) over channel i (c.f. section 3.3 and section 3.4). Then, the channels are ranked according to their weights and the best channel (i.e., the one providing highest $P_w^{(i)}$) will be used. Note that when the channel has high weight but at time t it is occupied, SURF reacts (i) by not transmitting the packet on the best weighted channel and (ii) by selecting the next best weighted channel for packet transmission/overhearing. Also note that when all the channels are occupied, no message is sent.

The increase of weight is related to the two objectives the SURF strategy needs to satisfy. The major objective of protecting the ongoing PR activity is mapped as a function of PR unoccupancy. The higher the probability of PRs being in OFF state, i.e. $PR_u^{(i)}$, the higher the weight will be. Thus, SURF gives high importance to not degrading the service of ongoing primary communications. The second objective of increasing connectivity is implemented in the second term of Eq.3.1. More precisely, the weight increases with the number of CR neighbors i.e. $CR_o^{(i)}$. In the following, we discuss in detail how the primary radio unoccupancy and cognitive radio occupancy could be estimated.

3.3 Primary Radio Unoccupancy

The primary radio activity, i.e. presence or absence of the PR signal, can be modelled as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [116–118]. This PR activity model has been used widely in the literature [76, 84, 116–118, 120–122]. The ON/OFF PR activity model approximates the spectrum usage pattern of public safety bands [84, 123]. The public safety band is designated for commercial and public safety uses [124]. The authors in [125] approximate and validate the PR ON/OFF activity model for the presence of the PR signal in IEEE 802.11b. The ON/OFF PR activity model is also the most famous model for voice [126]. An important feature of this ON/OFF PR activity model is that it captures the time period in which the channel can be utilized by CRs without causing any harmful interference to PR nodes [119]. Fig. 3.1 illustrates the wireless channel model and the state transition from ON to OFF state with probability (w.p.) equals 1 . The ON i.e. busy state indicates that the channel is currently occupied by the PR node, while the OFF i.e. idle state indicates that the channel is currently unoccupied by PR node. The binary sequence 1/0 corresponds to the ON and OFF state of the channel. Channel sensing is the sampling procedure of a given channel to discover its state through the number of transitions a channel follows (ON to OFF, OFF to ON, ON to ON, and OFF to OFF), as mentioned in [119].

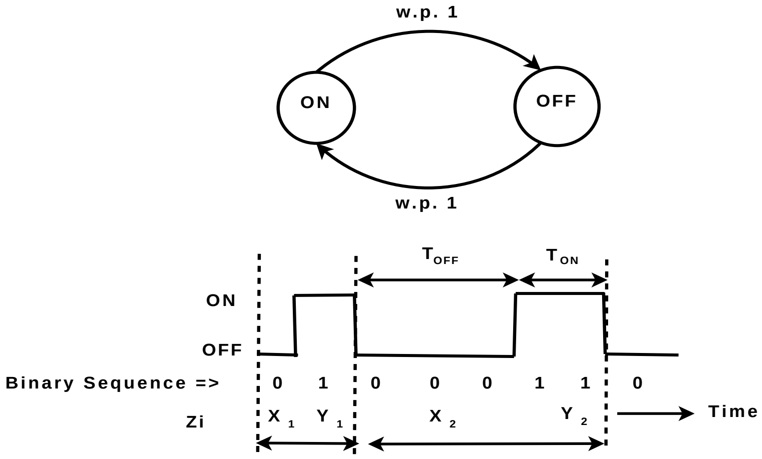


Figure 3.1: Wireless channel model: Alternating Markov Renewal Process for PR activity.

The duration of ON and OFF states of channel i are denoted as T^i_{ON} and T^i_{OFF}, respectively. The renewal period of a channel occurs when one consecutive ON and OFF period is completed. The duration of ON and OFF states are assumed to be i.i.d. random variables X_k and Y_k, k $\in \mathbb{N}$. Let Z_k denote the renewal period of channel i, such that $Z_k = X_k + Y_k$ [116, 118, 119, 127], where k $\in \mathbb{N}$.

Both ON and OFF periods are assumed to be independent and identically distributed (i.i.d.). Since each PR user arrival is independent, each transition follows the Poisson arrival process. In [116, 127], the authors proved that when each PR arrival follows a Poisson arrival process, the length of ON and OFF periods are exponentially distributed. In this chapter, we use the formulation of [116, 118, 119, 127] that the channels ON and OFF periods are both exponentially distributed with p.d.f. $f_X(t) = \lambda_X \times e^{-\lambda_X t}$ for ON state and $f_Y(t) = \lambda_Y \times e^{-\lambda_Y t}$ for OFF state.

The duration of time in which channel i is in ON state i.e. *channel utilization* u^i is given as [119] :

$$u^i = \frac{E[T^i_{ON}]}{E[T^i_{ON}] + E[T^i_{OFF}]} = \frac{\lambda_Y}{\lambda_X + \lambda_Y} \tag{3.2}$$

where $E[T^i_{ON}] = \dfrac{1}{\lambda_X}$ and $E[T^i_{OFF}] = \dfrac{1}{\lambda_Y}$. λ_X and λ_Y are the rate parameter for exponential distribution. $E[T^i_{ON}]$ and $E[T^i_{OFF}]$ are the mean of exponential distributions. Let $P_{ON}(t)$ be the probability of channel i in ON state at time t and $P_{OFF}(t)$ be the probability of channel i in OFF state at time t. The probabilities $P_{ON}(t)$ and $P_{OFF}(t)$ can be calculated as:

Table 3.1: Wireless channel parameters used in the simulation.

	Ch 1	**Ch 2**	**Ch 3**	**Ch 4**	**Ch 5**	**Ch 6**	**Ch 7**	**Ch 8**	**Ch 9**	**Ch 10**
λ_X	1.25	0.4	1	0.4	0.5	2	1	0.18	0.5	0.67
λ_Y	0.67	2	1	0.33	1	0.29	0.25	2	1.33	0.5
u^i	0.35	0.83	0.5	0.45	0.67	0.13	0.2	0.92	0.73	0.43

$$P_{ON}(t) = \frac{\lambda_Y}{\lambda_X + \lambda_Y} - \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-(\lambda_X + \lambda_Y)t} \tag{3.3}$$

$$P_{OFF}(t) = \frac{\lambda_X}{\lambda_X + \lambda_Y} + \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-(\lambda_X + \lambda_Y)t} \tag{3.4}$$

Thus, by adding Eq.3.3 and Eq.3.4, we get

$$P_{ON}(t) + P_{OFF}(t) = 1 \tag{3.5}$$

In fact, Eq.3.3 and Eq.3.4 provides the probability of ON and OFF respectively, at any time t, provided that the channel started at state=OFF at time 0. Since our goal is to select the channel that will be unoccupied at time t, from hereafter we will only consider $P_{OFF}(t)$. Each CR node locally computes these probabilities. The values of λ_X and λ_Y can be easily measured by CR nodes by collecting the historical samples of channel state transitions, as in [119]. These rate values can be measured from the sample of the number of transitions (ON to OFF, OFF to ON, ON to ON, and OFF to OFF) a channel follows, as mentioned in [119]. In this chapter, we are using the values measured by authors in [119] (cf. Table 3.1).

The best channel at time t is the one that has *very high probability of being in OFF state*. It may be possible that the probabilistically predicted next channel state mis-match with the current state of the channel, referred hereafter as wrong channel state prediction. This further leads to bad channel selection decision and causes harmful interference to PR nodes. Note that CR nodes keep the history of predicted and measured states of the channel. This history is maintained on each packet sending/receiving event. In our calculations, we did not consider any time window, and the value of N (cf. Eq. 3.6, 3.7, and 3.8) is calculated on each packet sending/receiving event. For the time being, we consider full history in our calculations and it is fixed. But it can also be adaptive. For instance, we can give importance to more recent observations by using the Exponentially Weighted Moving Average (EWMA) technique.

Note that we took the PR ON/OFF activity model from [118,119] and our contribution is that, we added the capability of learning of wrong prediction of channel availability to work in parallel with this PR activity model. Next, we detail how the learning of previous wrong prediction can help to tune future predictions.

3.3.1 Wrong Prediction of Channel Availability

Another challenge we deal with in this chapter resides in making efficient and reliable channel selection decisions on-the-fly and in recovering from bad channel selection decisions. Clearly, keeping track of wrong channel state predictions can help CR nodes to recover from their bad channel selection decisions, which ultimately enhance the reliability and the performance. Due to the *memoryless* property of the markov exponential model, there is a large degree of randomness and this results in imperfect prediction of channel state [84]. To deal with this *memoryless* property of the markov exponential model, CR nodes always keep calculating the next state of the channel, $P_{OFF}(t)$, with Equation 3.4. In parallel, CR nodes calculate $P^*_{OFF}(t)$ which considers the current state of the channel and wrong channel state predictions.

To achieve this goal, the nodes maintain the history of predicted channel states and the observed current state of the channels. CR nodes then compute which predictions were wrong and keep them in history. This history is then used to calculate the probabilities P_{UM} and P_{SM}. P_{UM} is defined as the probability that the predicted channel state mismatches with the actual channel state. Each CR node uses P_{UM}, while calculating the next channel state (cf. Fig. 3.2). Conversely, the probability of successfully matched state P_{SM} is defined as the probability that the predicted channel state matches with the current channel state. More precisely, the accuracy of the recovery mechanism of SURF depends upon the predicted state of the channel (cf. probability value given by Eq. (3.4)) and the measured current state of the channel. Table. 3.2 provide the possible combinations between the values of predicted state and current state of the channel. We estimate the state of the channel by taking as an estimation the more probable state between ON/OFF and then we compare the predicted state of the channel with the current state of the channel.

Table 3.2: Predicted and Current States of the Channel.

Event		Predicted State	Current State
P_{SM}		ON	ON
		OFF	OFF
P_{UM}	P_{MD}	OFF	ON
	P_{FA}	ON	OFF

The probability P_{SM} is expressed as:

$$P^{(i)}_{SM} = \frac{x_t}{N}, \tag{3.6}$$

where x_t is the number of times the predicted channel state matches with the actual channel state, and N is the total number of times the prediction occurs, and

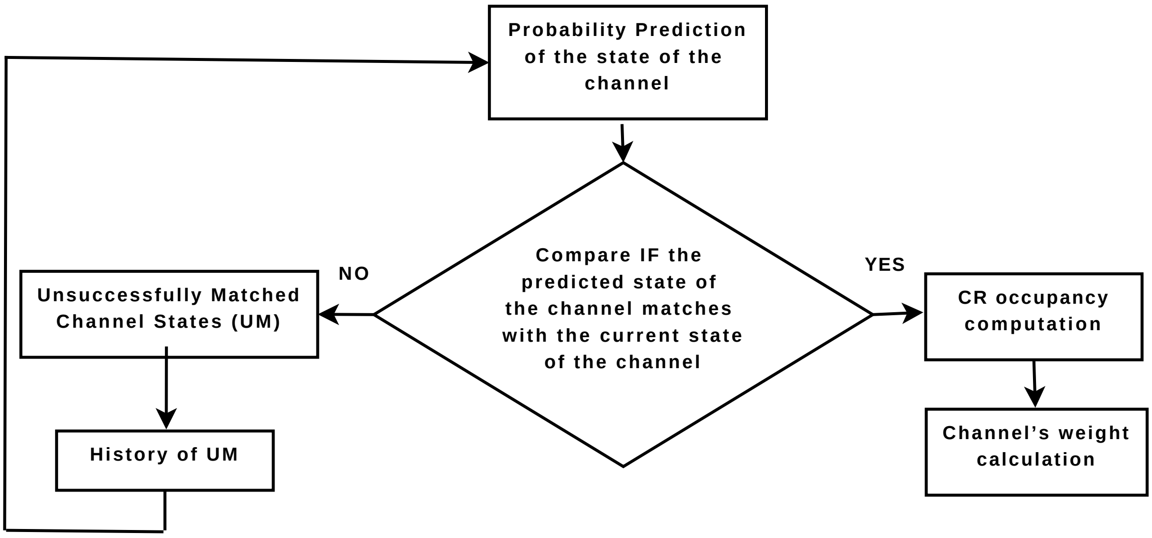


Figure 3.2: Flow chart showing the corrective measure taken by the CR nodes in the case of detection of unsuccessfully matched channel states i.e. P_{UM}.

The probability P_{UM} is expressed as:

$$P_{UM}^{(i)} = \frac{x_{nt}}{N}, \tag{3.7}$$

where x_{nt} is the number of times the predicted channel state does not match with the actual channel state i.e. how often the channel states predictions was erroneous, and N is the total number of times the prediction occurs. In fact, the P_{UM} measures two different types of channel states cases (cf. Table 3.2). The first one is the case when predicted channel state is OFF and the measured channel state is ON and the second one is the case when the predicted channel state is ON the measured channel state is OFF. Thus, we further decomposed P_{UM} into P_{MD} and P_{FA} as:

$$P_{UM}^{(i)} = \frac{x_{nt}}{N} = P_{MD}{}^{(i)} + P_{FA}{}^{(i)}, \tag{3.8}$$

where P_{MD} is the *Probability of Miss-Detection* and occurs when predicted channel state is OFF and the measured channel state is ON. In P_{MD}, CR node declares the busy channel as unoccupied. This will lead to harmful interference with PR nodes. While, P_{FA} is the *Probability of False-Alarm* and occurs when the predicted channel state is ON and the measured channel state is OFF. In P_{FA}, CR node declares that the unoccupied channel is busy. This will lead to refrain CR node from transmitting and thus, loose spectrum opportunity. P_{FA} and P_{MD} are measured by every CR node on per channel basis. In fact, CR node predicts the state of the channel and this predicted state is compared with the actual state of the channel. If the predicted state of the channel is ON and the measured channel state is OFF, CR node increases the P_{FA} counter, else if the predicted state of the channel is OFF and the measured state of the channel is ON, CR node increases the P_{MD} counter. Both the P_{FA} and P_{MD} counters are then divided by the total number of times the prediction occurs. In this manner, each CR node maintains the history of P_{FA} and P_{MD}. Note that all measurements about P_{FA} and P_{MD} were taken at each packet transmission/reception event.

Consequently, the lower the $P_{UM}(t)$, the more accurate will be the channel state prediction. Putting things together, we estimate $P^*_{OFF}(t)$, which considers the probability of unsuccessfully matched state during the channel state prediction, as follows:

$$PR_u^{(i)} = P^*_{OFF}(t)^{(i)} = P^{(i)}_{OFF}(1 - P^{(i)}_{FA}) + P^{(i)}_{MD}(1 - P^{(i)}_{OFF}) \tag{3.9}$$

where $PR_u^{(i)}$ is the primary radio unoccupancy, as mentioned in Eq. 3.1. In the case of a perfect channel prediction (i.e., $P_{FA} = 0$ and $P_{MD} = 0$), $P^*_{OFF}(t)$=$P_{OFF}(t)$. In the presence of channel prediction errors, the probability of channel i being in OFF state is given by Eq. (3.9).

3.4 Cognitive Radio Occupancy

CR occupancy reflects the number of CR neighbors using the channel. In fact, a good channel selection strategy is the one that tune CR nodes to the channel that have higher number of CR neighbors. Higher number of CR neighbors provides good level of network connectivity and consequently increase the transmission coverage of CR nodes. The CR occupancy $CR_o^{(i)}$ of channel (i) is calculated as:

$$CR_o^{(i)} = CR_n^{(i)} \tag{3.10}$$

where, $CR_n^{(i)}$ is the number of CR neighbors using the channel (i).

In order to calculate the CR occupancy, each CR node discovers their neighbors. Neighbors can be discovered in an efficient way by denominating the Common Control Channel (CCC), which will ensure the availability of common idle channel between CR nodes, and the neighbor discovery mechanism, as in [128]. In addition to neighbor discovery mechanism proposed in [128], SURF can jointly work with any other neighbor discovery mechanism, such as [129, 130].

3.5 Simulation Environment

In this section, we analyze the performance of SURF through extensive simulations.

3.5.1 Implementation Setup

We use the Cognitive Radio Cognitive Network (CRCN) patch [131] of NS-2 [132]. The CRCN patch has three building blocks that support cognitive radio functionalities in NS-2 (cf. Fig. 3.3). These building blocks are the cognitive radio network layer, the cognitive radio mac layer and the cognitive radio physical layer. The cognitive radio network layer is responsible for maintaining the neighbor list. It also makes the channel selection decision on the basis of the information provided by the cognitive radio MAC layer. The cognitive radio MAC layer supports multiple channels and keeps track of PR traffic, collision, interference information and it also maintains the channel list. The cognitive radio physical layer has information like transmission power, SINR/SNR physical model, propagation model etc. The information collected at different layers is shared through the information sharing layer.

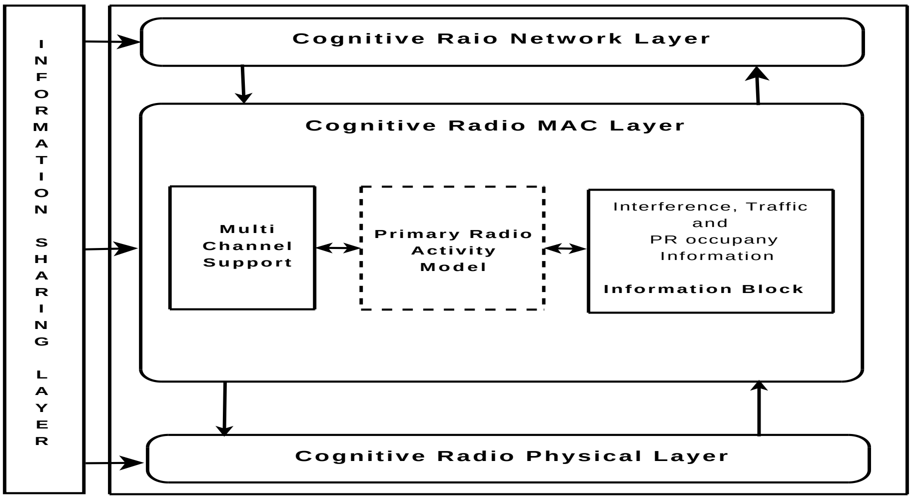


Figure 3.3: High level design of primary radio activity model in NS-2.

This CRCN patch of NS-2 does not model the activity of the PR nodes. Thus, we enhance the CRCN patch of NS-2 to include the PR activity model. Fig. 3.3 shows the high level design of PR activity model (dotted box) added in NS-2. The PR activity block is responsible for generating and keeping track of PR activities in each spectrum band (spectrum utilization) i.e., sequence of ON and OFF periods by PR nodes over the simulation time. These ON and OFF periods can be modelled as continuous-time, alternating

ON/OFF Markov Renewal Process (MRP) [116], [118]. The ON (busy) state means the channel is occupied by the PR node. While, the OFF (idle) state means the channel is unoccupied by the PR node. We consider the channels ON and OFF periods are both exponentially distributed, as in [118], [119]. The rate parameter λ_X and λ_Y (cf. Table 3.1) of the exponential distribution is provided as an input in the simulation, which were measured by authors in [119], [118]. Note that we took first nine values of the rate parameters λ_X and λ_Y from reference [119] and one value from reference [118]. Then, according to this rate parameter, channels follow the ON and OFF periods.

We consider a simple mac protocol (Maccon.cc), available with the CRCN patch of NS-2. This mac protocol is a multiple-channel, collision and contention-based mac protocol. Note that in the original state, the Maccon.cc mac protocol selects channel randomly from the predefined set of channels and the channel selection decision occurs at the mac layer. We now perform channel selection at the network layer. Thus, we modify this mac protocol and provide the capability to the network layer to make the channel selection decision. We further add channel selection strategies RD, HD, SB and SURF to the network layer, which we describe hereafter. Based upon any particular channel selection strategy, the network layer takes the channel selection decision. This channel selection decision is encapsulated in the network layer packet header and it is passed to the mac layer, which then switch to the channel based on the channel selection decision provided by the network layer.

In the Maccon.cc mac protocol, there are two channel states: $IDLE$ and $BUSY$. These states are dependent on the channel conditions and they are used by the mac protocol to handle the transmission and reception activities of CR nodes. $IDLE$ means that no activity is going on, on the channel and the channel is free to use for transmission by the CR node and $BUSY$ means that the channel is occupied by any undergoing CR transmission. In order to deal with the activities of the PR nodes, we include for each channel two more states at mac layer i.e., $PR\_OCCUPIED$ and $PR\_UNOCCUPIED$, indicating that the channel is occupied and unoccupied by the PR node, respectively. These two states of the channel will be checked each time by the mac protocol while performing transmission or overhearing.

3.5.2 Performance Metrics

We compare SURF with random strategy (RD), highest degree strategy (HD) and selective broadcasting, proposed in [90] with multiple transmissions (SB). We suggested RD strategy, which is the simplest one and no information is required. In RD, channels are randomly selected to be used by CR nodes for transmission and/or overhearing, without any consideration to the ongoing PR and CR activity over these channels. HD approach only considers CR activities and is inspired by SB approach. In HD, CR nodes select the highest CR degree channel for transmission and overhearing, without any consideration of PR activity. The highest degree channel covers, consequently, the highest number of neighbors in the available list of channels. In SB, each CR node calculates a minimum set of channels, Essential Channel Set (ECS), for transmission that covers all its geographic neighbors, without considering the PR unoccupancy. In SB, a CR node transmits on multiple channels in round-robin fashion present in the ECS list, until all neighbors are covered. Note that in [90] nothing is mentioned about how nodes overhear over the channels. Therefore, we consider nodes select for overhearing the highest degree channel from their ECS list only. If more than one option is available, a random choice for transmission/overhearing is performed among those channels with the same degree.

Since, our goal is to efficiently disseminate the data, tuning of sender and receiver nodes to the same channel with high probability, and to protect the PR nodes from harmful interference, we define five performance metrics:

1. *Harmful Interference Ratio (HIR)*: This metric is defined in order to capture the notion of collision with PR nodes. HIR is defined as the ratio of the total number of times the channel is occupied by PR node after the channel selection decision over total number of times the channel selection decision occurs.

2. *Average Delivery Ratio*: This metric is defined to effectively measure the data dissemination process. It is the ratio of packets received by a particular CR node over total number of packets sent in the network.

3. *Ratio of Accumulative CR Receivers*: This metric also evaluates the data dissemination process. It is defined as the average ratio of accumulative CR receivers per hop over the accumulative effective neighbors per hop. Accumulative CR receivers per hop are the number of CR receivers per hop that successfully received the message, while accumulative effective neighbors per hop are the CR neighbors that selects the same channel for overhearing as the sender node used for transmission. The ratio of accumulative CR receivers indicates the effect of collisions happen at each hop of communication. Note that by accumulative ratio we mean: at each new hop n, the receivers and effective neighbors of all previous hops $l < n$ are summed up to the ones at hop n.

4. *Ratio of Effective Neighbors and Ratio of Accumulative Effective Neighbors*: Ratio of effective neighbors are the number of neighbors that selects the same channel for overhearing as the sender node used for transmission over the total number of CR neighbors. While, ratio of accumulative effective neighbors are the effective neighbors

of all previous hops $l < n$ are summed up to the ones at hop n over the total number of CR neighbors of all previous hops $l < n$ are summed up to the ones at hop n.

3.5.3 Simulation Environment

The transmission range of CR nodes is set to $R = 250m$. The number of CR nodes is fixed to N=100 and CRs are randomly (uniformly distributed) deployed within a square area of $a^2 = 700\text{x}700m^2$. Simulations run for 1000 seconds. Total 1000 packets were sent, where each packet is sent by a randomly selected node after 1 second. All results are obtained with a confidence interval of 95%.

We consider 5 ($Ch = 5$) and 10 ($Ch = 10$) total number of channels, which allows varying the neighborhood density d_{avg} between 11.3 (when Ch=5) and 20.1 (when Ch=10). Note this density is computed *after* the spectrum sensing provides the list of available channels and *before* the CRs select the channel to transmit/overhear.

Ch means the total number of channels returned by the spectrum sensing. It is the maximum number of channels authorized per CR node. When the network initialize, we assign total number of channels to each CR node from the pool of the channels to include diversity in the number of available channel set. Total 5 channels are assigned to each CR node from the pool of 8 channels, and 10 channels are assigned to each CR node from the pool of 12 channels. If the pool is too large, the network may get disconnected, as no common channel id exists between the neighboring nodes. On the other hand, if the pool is same as the total number of channels, no notion of channel diversity is introduced. Note that channels are assigned randomly to CR nodes from the pool. Then, each CR node calculates the neighborhood density on each channel. After that, we take the average of neighbors on each channel per CR node ID basis.

To evaluate the impact of varying neighborhood density on SURF (cf. 3.6.2), we vary the average neighborhood density d_{avg} from 11.3 to 15.0 (when Ch=5) and from 20.1 to 26.8 (when Ch=10). In order to achieve this neighborhood density, we fixed the transmission range of CR nodes to $R = 250m$ and reduce the size of the network from $a^2 = 700\text{x}700m^2$ to $a^2 = 600\text{x}600m^2$. Since, the size of the network decreases, therefore TTL becomes $TTL = 5$.

Table 3.3 and 3.4 shows the average number of neighbors on each channel, when $Ch = 5$ and $Ch = 10$, respectively. When total number of channels, $Ch = 5$, each CR node can access 5 channels out of 8, and when total number of channels, $Ch = 10$, each CR node can access 10 channels out of 12. In this manner, when the number of channel increases, the average neighborhood density increases. Note that if we consider the same neighborhood density when $Ch = 10$, as we considered when $Ch = 5$, the network become disconnected. Thus, in order to ensure network connectivity, we consider 10 channels each CR node

Table 3.3: Average Number of Neighbors, when $Ch = 5$.

Channel ID	**Average Number of Neighbors**
0	7.66
1	14
2	11
3	12.2
4	13.7
5	10.1
6	12.3
7	8.66
d_{avg}	11.3

Table 3.4: Average Number of Neighbors, when $Ch = 10$.

Channel ID	**Average Number of Neighbors**
0	14.5
1	16.6
2	24.3
3	20.9
4	20.2
5	18.6
6	22.0
7	18.4
8	22.3
9	24.4
10	19.5
11	19.2
d_{avg}	20.1

can access out of 12 channels. In this case, it is worth mentioning that, at the following simulation studies, the neighborhood density varies in function of the CRs' channel selection and is lower than the above ones.

TTL is introduced to disseminate the message in the whole network. It is the maximum number of hops required for a packet to traverse the whole network, i.e., $\lceil \frac{2a}{R} \rceil$, and is set to $TTL = 6$ in our simulation scenario. Most papers used diagonal as the maximum length of the TTL to traverse the whole network. However, in order to ensure that the packet traverse the whole network, we consider the square area $2a$ as the value of the TTL, which covers larger area than the diagonal. Details on the used wireless channel parameters (rate of exponential distribution i.e., λ_X and λ_Y) can be found in Table. 3.1, which were measured by authors in [119]. These rate values can be easily measured from the sample of the number of transitions (ON to OFF, OFF to ON, ON to ON, and OFF to OFF) a channel follows, as mentioned in [119].

In summary, at each packet transmission event, the PR unoccupancy per channel i, ($PR_u^{(i)}$), is calculated by each CR node. Then, each CR node locally computes the CR occupancy ($CR_o^{(i)}$) and the weight ($P_w^{(i)}$) of each channel i. The channel with the highest weight is then selected for transmission and/or overhearing. The message dissemination phase then starts, in which a randomly selected CR node disseminates the message on the selected channel by setting a TTL at the message. CR neighbor nodes that are on the same channel will overhear the message, decrease the TTL, redo the spectrum sensing, select the best available channel, and disseminate the message to the next-hop neighbors until $TTL{=}0$.

In the following section, we perform comprehensive analysis of SURF. We first evaluate different parameters related to SURF in section 3.6. Then in section 3.7, we discuss and evaluate SURF by comparing it with three related approaches.

3.6 SURF Parameters Evaluation

We have defined P_{SM} as the probability of successfully matched state, and P_{UM} as the probability of unsuccessfully matched state, in Section 3.3.1. Moreover, we have also mentioned the number of tries by SURF when the channel is occupied in Section 3.2. In this section, our goal is to evaluate and understand them.

3.6.1 Tries in SURF

In this section, we evaluate different probabilities, such as P_{SM}, P_{UM}, P_{MD}, and P_{FA} (cf. section 3.3.1) and the number of tries by SURF. The number of tries means that when the channel has high weight but at time t it is occupied, SURF reacts by selecting the next best weighted channel for packet transmission.

Here, our goal of measuring these probabilities is to see how often SURF could use a channel at the 1^{st} try. If the 1^{st} try is greater than other tries, it means that the primary radio unoccupancy PR_U is computed in a good way. To verify this, we see in Fig. 3.4 that SURF is able to use the channel with a success rate of 49.57% and 58.00% at the 1^{st} try, when $Ch = 5$ and $Ch = 10$, respectively.

Fig. 3.4 shows the ratio of P_{SM}, P_{UM}, P_{MD}, and P_{FA} states and number of tries in SURF, when $Ch = 5$ and $Ch = 10$. Where P_{SM} is the probability of successfully matched state, P_{UM} is the probability of unsuccessfully matched state, P_{MD} is probability of misdetection, and P_{FA} is probability of false-alarm. Note that the sum of all the tries gives $P_{SM}{+}P_{UM}{=}1$ and $P_{UM}{=}P_{MD}{+}P_{FA}$. When $Ch = 5$, the P_{SM} and P_{UM} values can be seen in Table. 3.5. The sum of P_{SM} for all the tries is 68% and the sum of P_{UM} for all the tries is 32%. Hence, the sum of $P_{SM}{+}P_{UM}{=}68\%{+}32\%{=}100\%$ for $Ch = 5$. In the same manner, when $Ch = 10$, the P_{SM} and P_{UM} values are also shown in Table. 3.5. The sum of P_{SM} for all the tries is 70% and the sum of P_{UM} for all the tries is 30%. Hence,

Table 3.5: Number of tries and probability values.

Channels	Probability	1^{st} Try	2^{nd} Try	3^{rd} Try	4^{th} Try	5^{th} Try	Sum	
5	P_{SM}	49.57%	10.9%	3.81%	1.94%	1.63%	68%	100%
	P_{UM}	21.6%	6.37%	2.3%	1.2%	0.5%	32%	
10	P_{SM}	58%	9.4%	1.6%	0.5%	0.2%	70%	100%
	P_{UM}	22.5%	4.9%	1.69%	0.7%	0.2%	30%	

the sum of P_{SM}+P_{UM}=70%+30%=100% for $Ch = 10$.

At the 1^{st}-try, when $Ch = 5$, SURF has the ratio of 49.57% of P_{SM}, and 21.6% of P_{UM}. But when the number of channels increase to 10 i.e., $Ch = 10$, SURF has higher ratio of P_{SM} i.e., $P_{SM} = 58\%$, and the ratio of P_{UM} is 22.5%. This is due to the fact that a lower number of channels also reduce the chances for CR nodes finding PR-unoccupied channels for their transmission. When $Ch = 10$, the ratio of P_{SM} is 9.4% at the 2^{nd}-try, the number of tries decrease and as we can see in the figure that at the 5^{th}-try, the ratio is almost 0.2%. This clearly shows that SURF is able to find unoccupied channels at the 1^{st} and 2^{nd} tries.

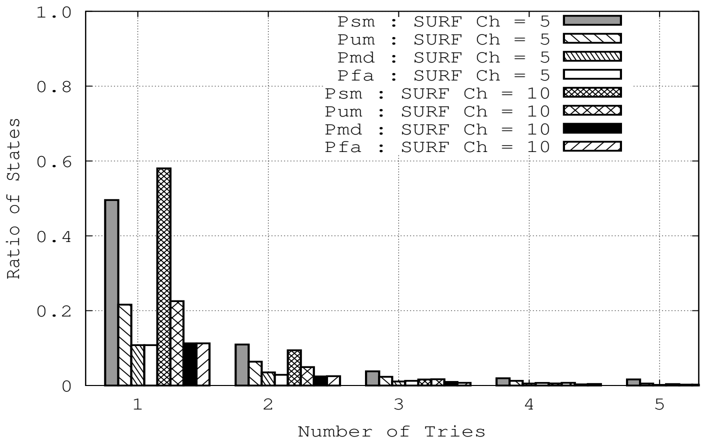


Figure 3.4: Ratio of P_{SM}, P_{UM}, P_{MD}, and P_{FA} states and number of tries in SURF.

3.6.2 Impact of Varying Neighborhood Density on SURF

Fig. 3.5 shows the percentage of messages received by percentage of CR nodes in SURF, under varying neighborhood density. SURF increases the reachability of CR nodes with the increase of average neighborhood density. More precisely, when the average node density increases from 11.3 to 15.0 ($Ch = 5$), higher number of CR nodes receives higher number of messages. But when $Ch = 10$, since we have higher number of channels, the number of nodes are more spread over the channels, so the increase of average node density from 20.1

Table 3.6: Overall average delivery ratio (in %).

	PR=0		*PR* $\neq 0$ *(cf. Table 3.1)*	
Strategy Name	**Ch=5**	**Ch=10**	**Ch=5**	**Ch=10**
RD	0.25 %	0.16 %	0 %	0 %
HD	0.18 %	0.18 %	0.02 %	0.02 %
SB	0.02 %	0.03 %	0 %	0 %
SURF	0.34 %	0.33 %	0.27 %	0.36 %

to 26.8 not necessarily increases the number of receivers.

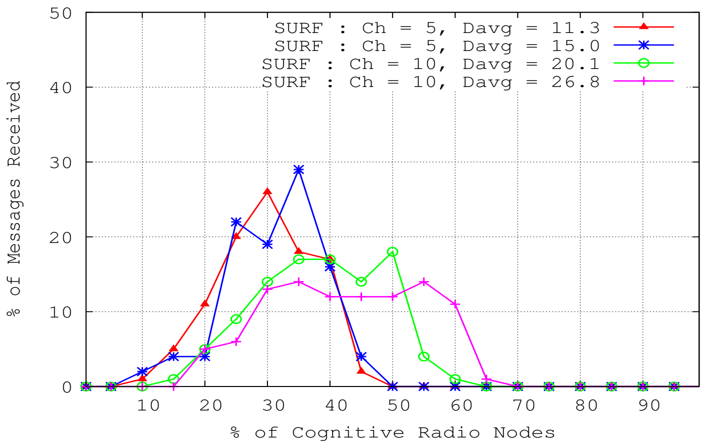


Figure 3.5: Percentage of Messages received by percentage of CR nodes in SURF under varying node density.

3.6.3 PR Utilization of the Selected Channel

As mentioned earlier that when the channel has high weight but at time t it is occupied, SURF reacts in this case (i) by not transmitting the packet on the best weighted channel and (ii) by selecting the next best weighted channel for packet transmission/overhearing. Also note that when all the channels are occupied, no message is sent. We now evaluate SURF by looking at the PR utilization of the selected channel and the number of try for each sent message. PR utilization means the PR activity on the selected channel. Note that there were 1000 total messages sent. In Fig. 3.6 and Fig. 3.7, we plot for each sent message, the try and the PR utilization of the selected channel by SURF.

Fig. 3.6 and Fig. 3.7 show the PR use of the selected channel by SURF, when $Ch = 5$ and $Ch = 10$, respectively. When $Ch = 5$ (cf. Fig. 3.6), we see that most of the time

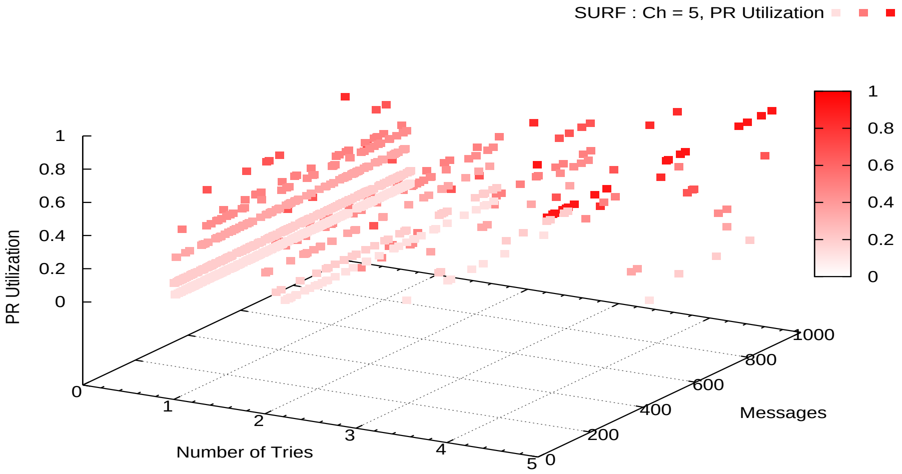


Figure 3.6: Sent Messages, tries, and the PR utilization of the selected channel in SURF, when Ch=5.

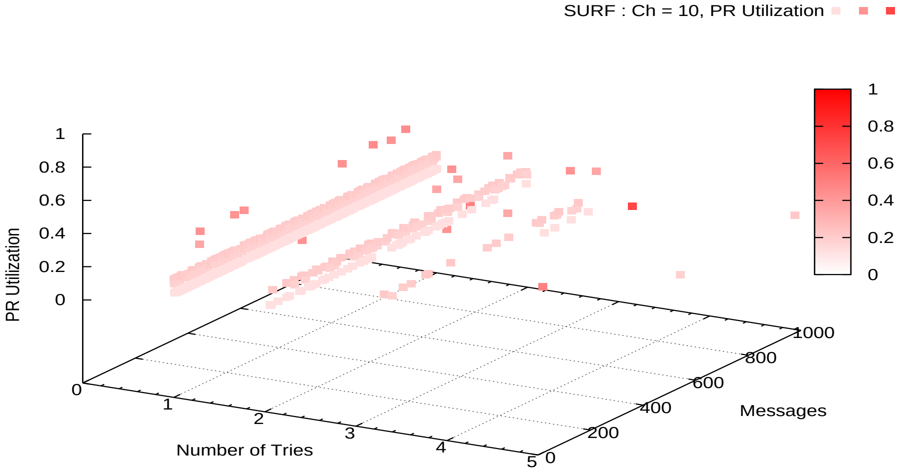


Figure 3.7: Sent Messages, tries, and the PR utilization of the selected channel in SURF, when Ch=10.

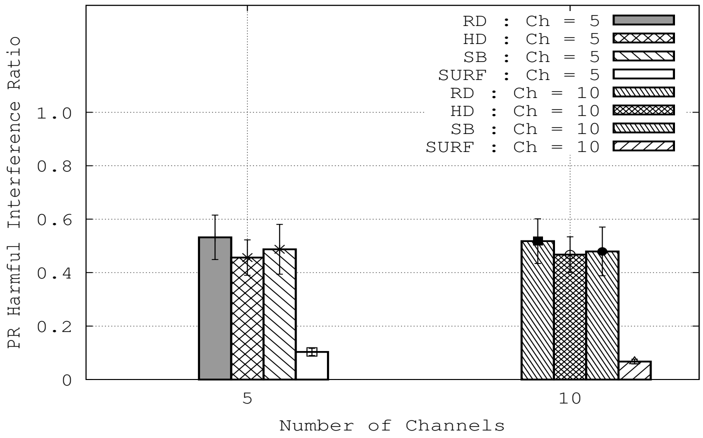


Figure 3.8: PR harmful interference ratio for RD, HD, SB and SURF, when Ch=5 and Ch=10.

SURF selects the channel at the 1^{st} try and the PR utilization of the selected channel is also low. But there are some rare cases where SURF selects a PR occupied channel and we can also see that there are very few cases when SURF goes to 3^{rd} and 4^{th} try. This is due to the fact that a lower number of channels also reduces the chance for CR nodes finding PR-unoccupied channels for their transmission. But when the number of channels increases to 10, i.e., $Ch = 10$, SURF selects the least PR utilized channel and almost all messages are sent at the 1^{st} or 2^{nd} tries.

3.7 SURF Comparison

In this section, we evaluate the performance of SURF by comparing it with three related approaches i.e., Random (RD), Highest Degree (HD), and Selective Broadcasting (SB).

3.7.1 Protection to Primary Radio Nodes

In this section, we characterize the probable interference caused by CR transmissions to PR nodes for SURF, RD, HD, and SB. Fig. 3.8 compares the harmful interference ratio for the four strategies i.e. RD, HD, SB and SURF, for Ch=5 and Ch=10. It can be clearly seen in the figure that SURF, as expected, causes less harmful interference to PR nodes, compared to RD, HD, and SB. This is primarily because, when using SURF, CR nodes select those channels that have very high probability of being in OFF state, reducing thus PR interference. Note that in SURF, if all channels are occupied, the CR transmission will not take place. In addition, when the number of channels is low, i.e. Ch=5, the value of

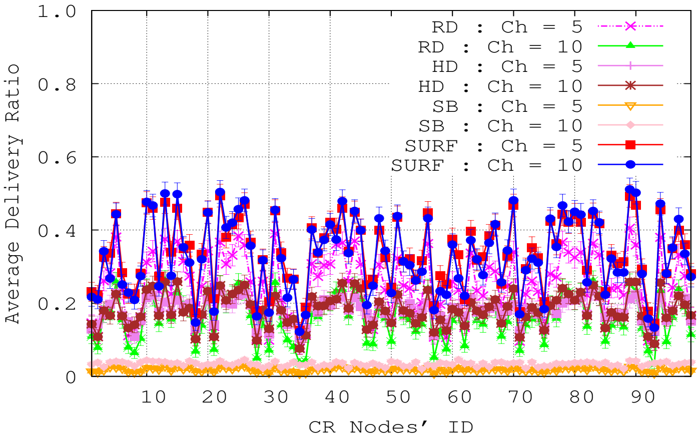


Figure 3.9: CR Nodes' ID and average delivery ratio, when PR activity is zero.

HIR is higher than Ch=10. This is due to the fact that a lower number of channels also reduces the chances for CR nodes finding PR-unoccupied channels for their transmission. As a result, SURF protects PR nodes, by reducing the amount of collisions with primary radios.

3.7.2 Robust Data Dissemination

In this section, our goal is to evaluate the reliability of data dissemination. We have chosen two parameters to evaluate robust data dissemination: (1) average delivery ratio, and (2) ratio of accumulative receivers.

Average Delivery Ratio: In order to better observe the impact on delivery ratio of such dynamic neighborhood, we first consider a scenario where PR activity equals to 0. Fig. 3.9 shows the average delivery ratio per node ID for Ch=5 and Ch=10 when PR activity equals to 0. The results attest the obtained low delivery ratios are mainly due to the creation of different topologies resulted from the multi-channel availability and distributed channel selection by CRs. More specifically, even when no PR competition exists, the maximum average delivery ratio is lower than 35%.

It is worth mentioning that the diversity in terms of available channels and PR activities, and the consequent lower neighborhood density after CRs local channel selection result in the creation of different topologies (i.e., dynamic neighborhood) at each transmission/overhearing of CR nodes. These issues make hard the achievement of a higher delivery ratio than SURF, as it can be observed in Fig. 3.9.

We now consider PR activity in our analysis. Fig. 3.10 compares the average delivery

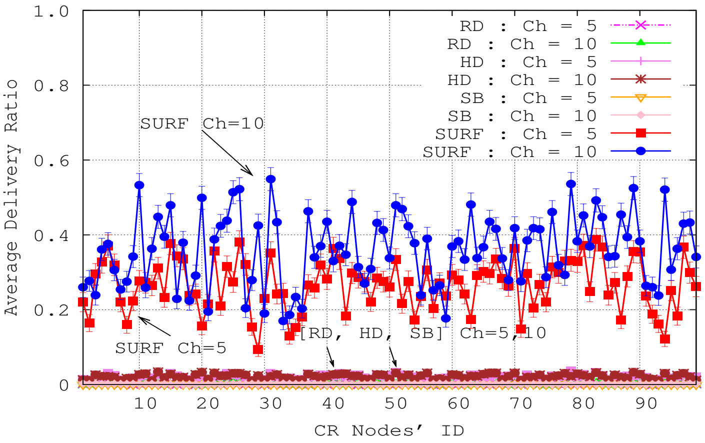


Figure 3.10: CR Nodes' ID and average delivery ratio.

ratio of RD, HD, SB and SURF, for Ch=5 and Ch=10. SURF increases considerably the delivery ratio compared to the other solutions. In particular, for Ch=5, SURF guarantees a maximum delivery ratio of approximately 40% compared to almost 0% in the case of RD, HD, and SB. And when Ch=10, SURF allows some nodes to reach a maximum delivery ratio of 50%, while in RD, it is almost 0% and 2% in HD and SB. In fact, RD, HD, and SB, do not guarantee that the selected channel is unoccupied for transmission thus causing a severe decrease in the delivery ratio. While in SURF, the average delivery ratio is higher because CR nodes select the channel that has higher $P^*_{OFF}(t)$ and higher CR neighbors. Nevertheless, it is worth noting that SURF is the approach less impacted by the PR activities: By intelligently taking profit of channels availabilities, SURF is able to ensure a stable delivery ratio even when CRs transmission is competing with the PR ones. Similarly, Table 3.6 summarizes the overall average delivery ratio of Fig. 3.9 (without PR activity) and Fig 3.10 (with PR activity).

Most importantly, it is worth noting that with the increase of the number of channels, SURF performance is also enhanced. This result is counterintuitive since adding more channels makes the synchronization between the sender and the receiver (i.e., selecting the same channel) harder to achieve. However, by using the appropriate metric and mainly employing the same strategy at the sender and the receiver, SURF achieves better results when more channels are available.

Ratio of Accumulative Receivers: Fig. 3.11 compares the ratio of accumulative receivers at each hop of communication (i.e., until $TTL = 0$) for RD, HD, SB, and SURF. SURF outperforms the three other techniques in all hops. At the 1^{st}-Hop, due to the first transmission of the message, no collision is present. In this case, SURF provides a ratio of

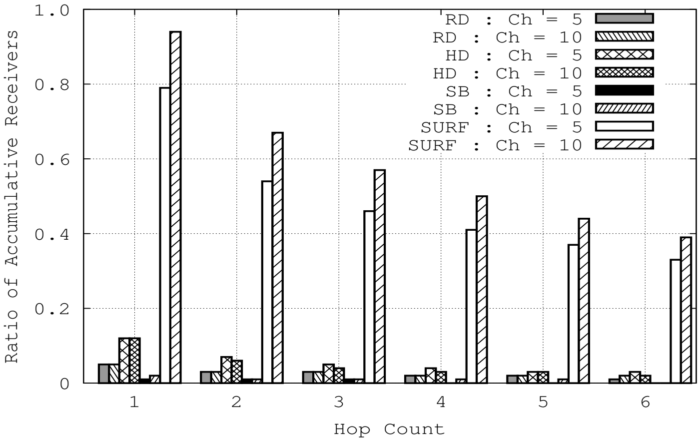


Figure 3.11: Hop count and Ratio of accumulative receivers.

95% receivers for Ch=10 (80% for Ch=5), against 5% for RD, 12% for HD, and 2% for SB. With the message propagation and its natural replication in the network, the probability of collisions increases and consequently, the receivers' ratio at each new hop decreases, for all the strategies. Still, SURF provides a better dissemination ratio than other strategies. This is obtained thanks to the SURF channel selection, which selects channels providing high probability for good delivery as well as for good reception.

In summary, results in Fig. 3.10 and Fig. 3.11 confirm that SURF can provide good network reachability, suitable for increasing dissemination reliability in multi-hop cognitive radio ad-hoc networks.

3.7.3 Tuning of Sender and Receiver

In this section, we evaluate and characterize the tuning of sender/receiver nodes. We have defined two metrics: (1) ratio of average effective neighbors, and (2) ratio of average accumulative effective neighbors (cf. section 3.5.2).

Fig. 3.12 compares the ratio of average effective neighbors over the total average number of CR neighbors of RD, HD, SB and SURF, for Ch=5 and Ch=10. SURF has higher ratio of effective neighbors compared to RD and SB, while almost equal ratio of effective neighbors to HD. This is primarily because SURF and HD prefer to select those channels that have higher number of neighbors. Since, SURF also considers PR unoccupancy (cf. Fig. 3.8), therefore, majority of transmissions are successful, which is not the case in HD (cf. Fig. 3.11). Moreover, this also results in the decrease of the delivery ratio and the ratio of accumulative receivers (cf. Fig. 3.10 and Fig. 3.11). This justifies that SURF is able to tune both sender and receiver to the right channel with high probability for effective and

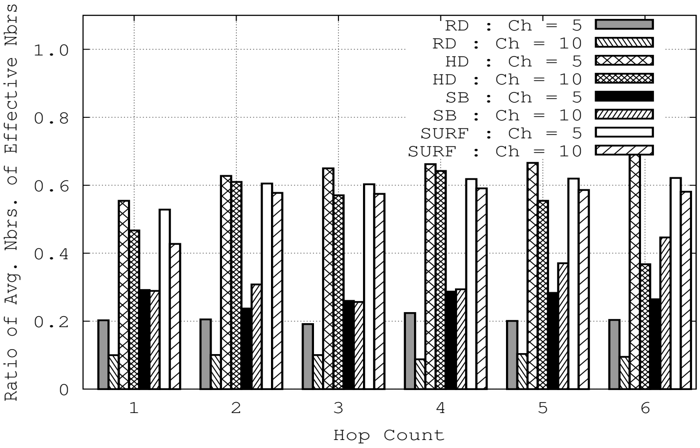


Figure 3.12: Ratio of Average Number of Effective Neighbors for RD, HD, SB and SURF.

robust data dissemination in multi-hop context.

Fig. 3.13 compares the ratio of average accumulative effective neighbors over the average accumulative total CR neighbors of RD, HD, SB and SURF, for Ch=5 and Ch=10. It is worth mentioning that CRs local channel selection result in the creation of different topologies (i.e., dynamic neighborhood) at each transmission/overhearing of CR nodes. As can be clearly seen in the figure that at the $6^{th} - Hop$, RD is only able to create a connected topology of 20% ($Ch = 5$) and 9% ($Ch = 10$) nodes in the network. SB is able to create a topology of 27% ($Ch = 5$) and 32% ($Ch = 10$) nodes in the network. HD is able to create a connected topology of 63% ($Ch = 5$) and 54% ($Ch = 10$), while SURF is able to create a connected topology of 60% ($Ch = 5$) and 56% ($Ch = 10$) nodes in the network.

Table 3.7: Packet Ratio Description.

Received Packets	Ratio of the total number of nodes that received the packets and total number of neighbor nodes
Missed Packets	Ratio of the total number of nodes that did not receive the packets (due to the selection of a different channel) and the total number of neighbor nodes
Interrupted Packets	Ratio of the total number of nodes that did not receive the packets (due to PR activity) and the total number of neighbor nodes

3.7.4 Packet Ratio

We now analyze the performance of RD, HD, SB, and SURF by evaluating the packet ratio of different types, e.g., received, missed, and interrupted packet ratio. We measure the packet ratio in single-hop context and multiple-sources are considered throughout the

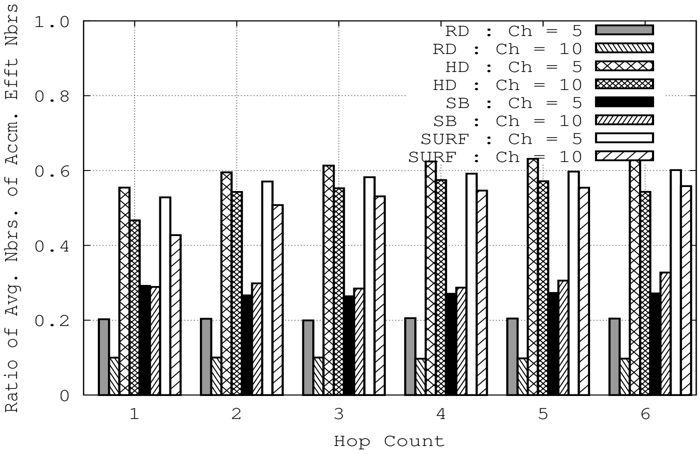


Figure 3.13: Ratio of Average Number of Accumulative Effective Neighbors for RD, HD, SB and SURF.

network. Table 3.7 shows packet ratio description used in the simulation. The received packet ratio is used to quantify the data dissemination success, missed packet ratio is used to quantify the packet losses due to nodes overhearing on different channel, while interrupted packet ratio is used to quantify the harmful interference to PR nodes.

Fig. 3.14 and Fig. 3.15 compares the packet ratio of RD, HD, SB and SURF, when Ch=5 and Ch=10, respectively. The packet received ratio of SURF is higher compared to RD, HD, and SB. This is primarily because SURF emphasis on selecting those channels that has higher number of neighbors. Note that the packet received ratio of SB is almost 0% because of overhearing on different ECS channel set. Conversely, due to the same reason, an opposite behavior can be seen in the packet missed ratio i.e. the packet missed ratio of SURF is lower than RD and HD. The packet missed ratio of SURF is 60% because nodes selects channels based upon their local observations. Note that when the number of channels increases from Ch=5 to Ch=10, the missed packet ratio of SB increases. This is due to the fact that when the number of channels increases in SB, the CR neighbors are spread over more channels and when the node broadcast on the channel, there are more chances that the CR neighbors miss the packet being overhearing on different channel. Both the packet received ratio and packet missed ratio reveals that SURF better disseminates the packets to the neighboring nodes, compared to RD, HD, and SB approaches.

The interrupted packet ratio in Fig. 3.14 and Fig. 3.15 shows that SURF drops less number of packets compared to RD, HD, and SB. This is due to the fact that SURF considers PR activity, while selecting the channel for transmission. More particularly, in SURF, the interrupted packet ratio decreases, when the number of channels increase from

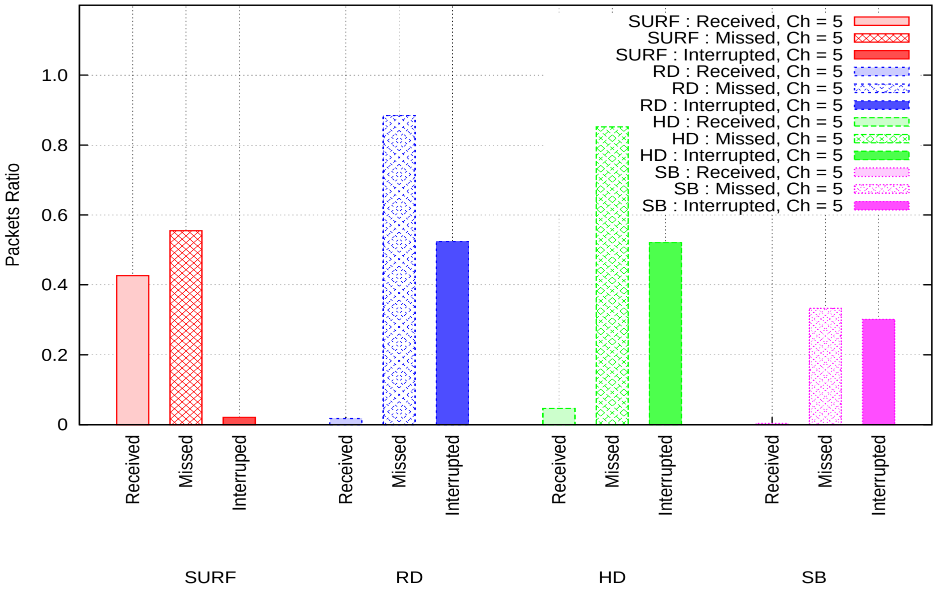


Figure 3.14: Packet Ratio for SURF, RD, HD, and SB when Ch=5.

$Ch = 5$ to $Ch = 10$. This is primarily because when the number of channels increase, SURF has higher chances to find the PR unoccupied channels.

3.8 Conclusion

In this chapter, we have introduced SURF, an intelligent and distributed channel selection strategy for robust data dissemination in multi-hop cognitive radio ad-hoc networks. The main design objective of SURF is the protection of primary radio nodes against harmful interference by CR transmissions and the increase of dissemination reliability in cognitive radio ad-hoc network. These two goals were achieved by classifying the channels on the basis of primary radio unoccupancy and the number of cognitive radio neighbors using each channel. Simulation results in NS-2 confirmed that SURF, when compared to random-based, higher degree, and selective broadcasting strategies, is effective in selecting the best channels. Furthermore, we show that unlike other solutions, the SURF performance is enhanced when increasing the number of existing channels. This is due to its intelligent selection mechanism.

Practical cognitive radio networks deployment suffers from different primary radio nodes activity patterns. This primary radio nodes activity pattern varies with underlying PR technology, time, and geographical location. Thus, in the following chapter, we focus and

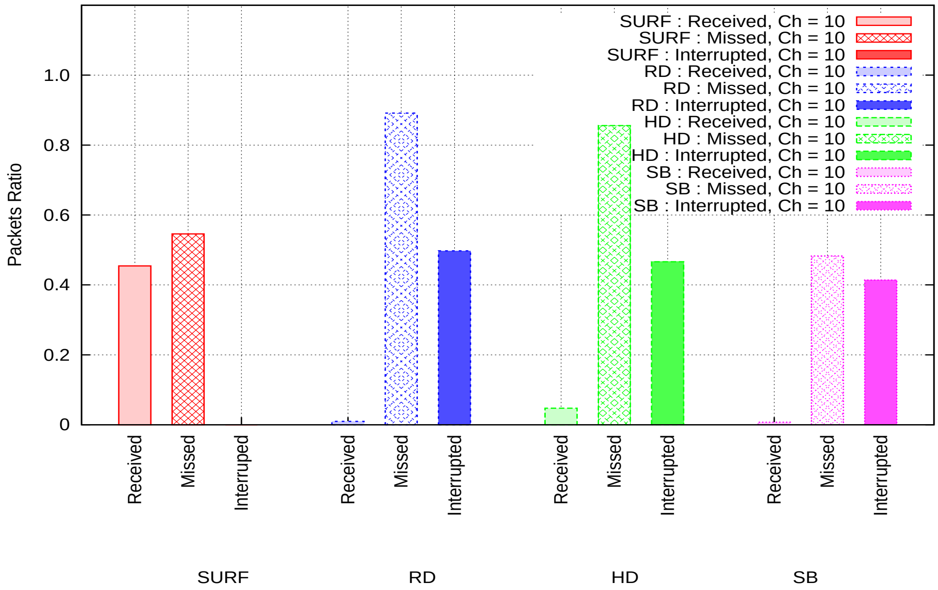


Figure 3.15: Packet Ratio for SURF, RD, HD, and SB when Ch=10.

study the impact of primary radio nodes activity on channel selection strategies.

Chapter 4

Impact of Primary Radio Nodes Activity on Channel Selection Strategies

Contents

In the previous chapter, we have presented SURF. We observed that SURF outperformed other channel selection strategies. However, the performance of SURF and other channel selection strategies are highly dependent upon the PR nodes activity pattern. Therefore, in this chapter, our goal is to analyze the impact of PR nodes activity pattern on different channel selection strategies.

The remainder of this chapter is organized as follows: Section 4.1 gives an introduction. Section 4.2 give a brief over of channel selection strategies i.e. RD, HD, SB, and SURF. In section 4.3, we discuss the PR nodes activity patterns. Performance evaluation is done in section 4.4, improvements regarding SURF is suggested in section 4.5 and finally, section 4.6 concludes the chapter.

4.1 Introduction

The performance of cognitive radio network is highly dependent upon the primary radio nodes activity pattern. The primary radio nodes activity pattern i.e. presence or absence of the PR signal, can be modeled as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [116–118]. This PR activity model has been used very widely in the literature [116–118].

Recently, very few works has been done to analyze PR nodes activity pattern. In [133], the authors model and evaluate the performance of Transmission Control Protocol over Cognitive Radio Ad Hoc Networks. The authors considered a single-hop topology for PR activity analysis and four different regions (long term, high, low, and intermittent) for PR nodes activity. The effect of PR ON/OFF periods on the system performance in the context of MAC protocol is evaluated in [134]. In [135], the authors studied the influence of the activity patterns of the primary radio transmitters on the area in which cognitive radios have opportunities for spectrum reuse, with the given transmit power. But none of these works have analyzed the impact of different PR nodes activity patterns on different channel selection strategies as well as on data dissemination. Moreover, these works do not consider the effect of PR nodes activity in a multi-hop network. In fact, due to lack of centralized entity and the difficult coordination between CR nodes in multi-hop cognitive radio ad-hoc network, the selection of a common channel by CR transmitters and receivers is a challenging task.

In this chapter, we study and analyze the impact of different PR nodes activity patterns on different channel selection strategies i.e. Random (RD), Highest Degree (HD), Selective Broadcasting (SB) and our proposed channel selection strategy (SURF). Moreover, we also analyzed how these channel selection strategies respond to different PR activity patterns. In particular, by analyzing our channel selection strategy SURF [34] under different PR activity patterns (wireless environments), we gain insights that will help us in future to set up different channel heuristics. Through extensive NS-2 simulations, we generate different PR activity patterns and investigate through several performance parameters how the approaches react.

4.2 Channel Selection Strategies

We consider four channel selection strategies i.e. Random (RD), Highest Degree (HD), Selective Broadcasting (SB), and our proposed channel selection strategy (SURF). We now describe each of them.

In RD approach, channels are randomly selected to be used by CR nodes for transmission and/or overhearing, without any consideration to the ongoing PR and CR activity over these channels.

In SB [90], each CR node calculates a minimum set of channels, Essential Channel Set (ECS), for transmission that covers all its geographic neighbors, without considering the PR unoccupancy. In SB, a CR node transmits on multiple channels in round-robin fashion present in the ECS list, until all neighbors are covered. Note that in [90] nothing is mentioned about how nodes overhear over the channels. Therefore, we consider that nodes select for overhearing the highest degree channel from their ECS list only. If more than one option is available, a random choice for transmission/overhearing is performed among those channels with the same degree.

HD approach only considers CR activities and is inspired by SB approach. In HD, CR nodes select the highest CR degree channel for transmission and overhearing, without any consideration of PR activity. The highest degree channel covers, consequently, the highest number of neighbors in the available list of channels.

SURF is our distributed channel selection strategy specifically designed for data dissemination in multi-hop cognitive radio networks. More details about the working principle of SURF can be found in chapter 3.

4.3 Primary Radio Nodes Activity Pattern

The primary radio nodes activity, i.e. presence or absence of the PR signal, can be modeled as a continuous-time, alternating ON/OFF Markov Renewal Process (MRP). More details about the PR activity modelling can be found in section 3.3.

We consider four different PR nodes activity patterns [133, 134], described as follows (see Fig. 4.1):

- Long Term PR Activity: In Long Term PR Activity, the channel has long ON and

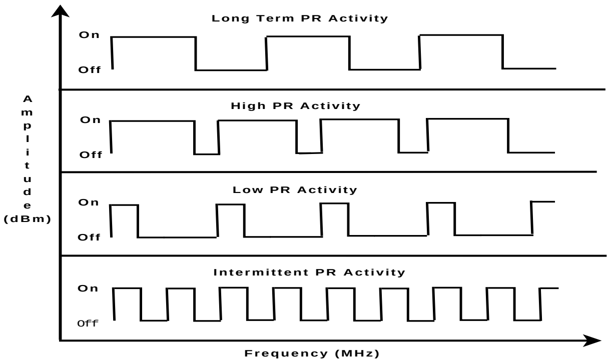


Figure 4.1: Long term, high, low and intermittent PR nodes activity.

long OFF periods. This type of PR activity can be seen in the scenarios where primary radio nodes subscribed to free call packages ($\lambda_X \leq 1$ and $\lambda_Y \leq 1$).

- High PR Activity: In High PR Activity, the channel has long ON and short OFF periods. This type of PR activity can be seen in highly congested urban environments or in rush hours, where all the channels are mostly occupied ($\lambda_X \leq 1$ and $\lambda_Y > 1$).

- Low PR Activity: In Low PR Activity, the channel has short ON and long OFF periods. This type of PR activity can be observed in remote areas or during less peak hours ($\lambda_X > 1$ and $\lambda_Y \leq 1$).

- Intermittent PR Activity: In Intermittent PR Activity, the channel has short ON and short OFF periods. This type of PR activity can be observed where users use the channels for very short period of time, e.g., bus stations, railway stations etc., ($\lambda_X > 1$ and $\lambda_Y > 1$).

Fig. 4.1 depicts an example of these four activity patterns. In order to achieve such PR nodes activity, we vary the rate parameter λ_X and λ_Y of the exponential distributions, as indicated in Table 4.1 [133, 134].

Table 4.1: Primary Radio Activity.

PR Activity	ON	OFF	λ_X	λ_Y
Long Term Activity	$\lambda_X \leq 1$	$\lambda_Y \leq 1$	Long ON	Long OFF
High Activity	$\lambda_X \leq 1$	$\lambda_Y > 1$	Long ON	Short OFF
Low Activity	$\lambda_X > 1$	$\lambda_Y \leq 1$	Short ON	Long OFF
Intermittent Activity	$\lambda_X > 1$	$\lambda_Y > 1$	Short ON	Short OFF

4.4 Performance Analysis

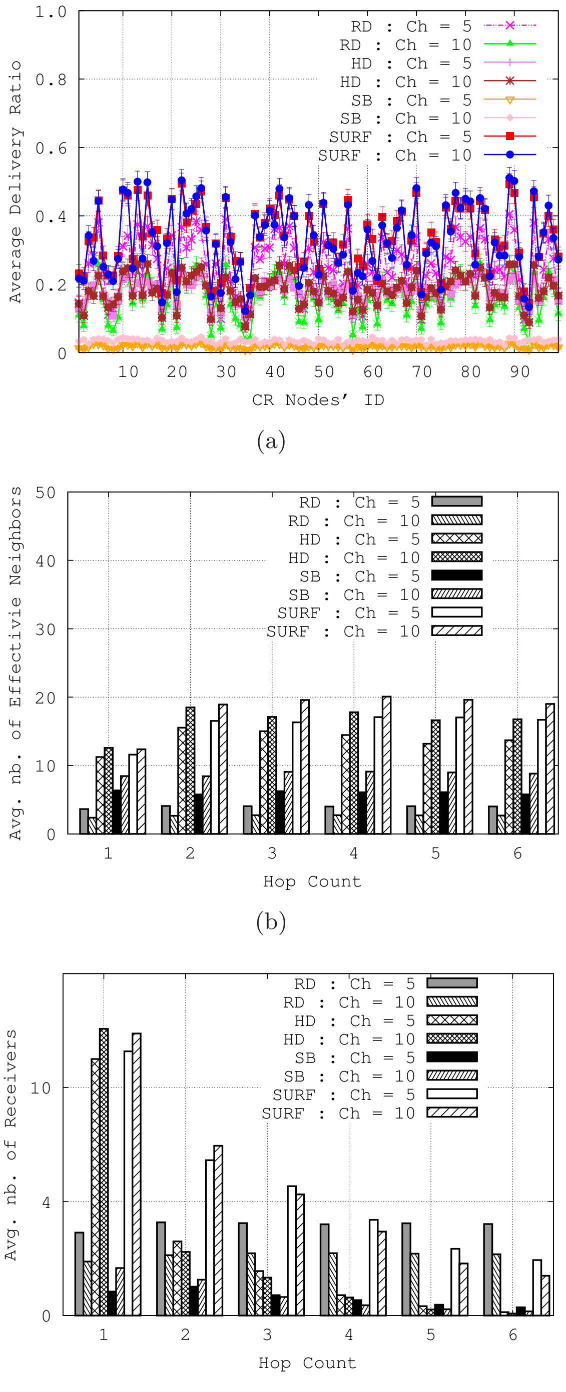
This section presents the performance analysis of the fours channel selection strategies under varying PR nodes activity. To achieve this, we performed extensive NS-2 simulations. For this end, three performance metrics are considered: Harmful Interference Ratio (HIR), Average Delivery Ratio, and Ratio of Accumulative CR Receivers (cf. section 3.5.2 for their definitions).

The number of CR nodes is fixed to N=100. CRs are randomly deployed within a square area of $a^2 = 700\text{x}700m^2$ and their transmission range is set to $R = 250m$. Simulations run for 1000 seconds and a total of 1000 packets are sent, where each packet is sent by a randomly selected node at an interval of 1 second. All results are obtained with a confidence interval of 95%.

We consider 5 ($Ch = 5$) and 10 ($Ch = 10$) total number of channels, which allows varying the neighborhood density d_{avg} between 11.3 (when Ch=5) and 20.1 (when Ch=10). Note this density is computed *after* the spectrum sensing provides the list of available channels and *before* the CRs select the channel to transmit/overhear. In this case, it is worth mentioning that, at the following simulation studies, the neighborhood density varies in function of the CRs' channel selection and is lower than the above ones. The results attest the obtained low delivery ratios are mainly due to the creation of different topologies resulted from the multi-channel availability and distributed channel selection by CRs. This can be verified in the Fig. 4.2, which shows results for delivery ratio, number of receivers and of effective neighbors, for Ch=5 and Ch=10 *when no PR nodes activity is present in the channels.* As can be observed, even when CR nodes do not have to compete with PR nodes to have access to the channels, the average delivery ratio ranges from $35\% - 50\%$, the average number of effective neighbors ranges from $10 - 20$ and the average number of receivers ranges from $12 - 2$ (from 1^{st} to 6^{th} hop) in SURF.

Fig. 4.3–Fig. 4.6 show the graphs for varying PR nodes activity patterns. Similarly, Table 4.2 summarizes the harmful interference ratio of Fig. 4.3–Fig. 4.6. In Long Term PR activity, besides of guaranteeing lower HIR compared to RD, HD, and SB, SURF also ensures a higher delivery ratio than such approaches. In High PR activity, all the channels are highly occupied, and consequently, very less chance for communication is let to all the approaches. Nevertheless, SURF is able to manage very low HIR and still have some delivery ratio (2% around), compared to the other approaches.

It is clear that when PR activity is very low (cf Fig. 4.5) every strategy behaves well in term of HIR (cf. 4.5(a)). In this case, SURF helps select the best channel in term of CR connectivity, i.e., delivery ratio to CR (cf. Fig. 4.5(b)), while generates very less or almost zero HIR, when compared to RD, SB, and HD. The receivers ratio is also the highest for



(a)

(b)

(c)

Figure 4.2: Zero Primary Radio Activity. (a) CR Nodes' ID and average delivery ratio for RD, HD, SB and SURF. (b) Hop count and average number of effective neighbors for RD, HD, SB and SURF. (c) Hop count and average number of receivers for RD, HD, SB and SURF.

Table 4.2: Harmful Interference Ratio (HIR) (in %) under various Primary Radio Nodes Activity.

	RD		*HD*		*SB*		*SURF*	
	Ch=5	**Ch=10**	**Ch=5**	**Ch=10**	**Ch=5**	**Ch=10**	**Ch=5**	**Ch=10**
Long Term	63	53	51	49	50	50	23	27
High	90	87	86	83	89	89	60	65
Low	17	16	13	12	18	13	5	5
Intermittent	61	49	47	46	58	56	22	22

SURF.

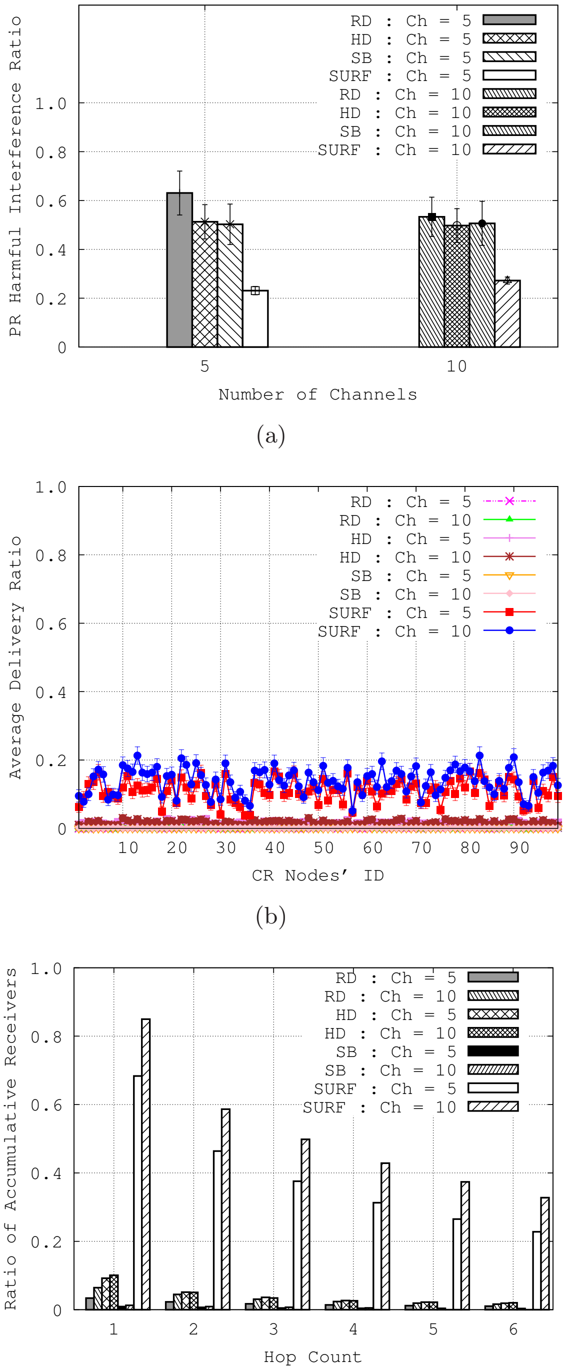
Unsurprisingly, the best performance gain is observed in the intermittent case when using SURF: Lower HIR and higher delivery ratio is provided than RD, HD, and SB. It is worth noting that, in the cases where short ON for PR nodes is considered (i.e., in intermittent or low activity scenarios), all the approaches perform the better. However, the channel selection mechanism provided by SURF could find the best spectrum opportunities in all considered cases, while respecting the PR nodes activities.

The Main Conclusions are:

- When the system is free (Low PR activity), every solution offers a comparable performance. Sometimes a clever solution does not worth it due to the complexity it introduces.
- When the system is close to maximum capacity (High PR activity), all solutions have bad performance. When channels are fully occupied by PRs there is no real opportunity for transmission, here also the gain is very low compared to the complexity of the solutions.
- Intermittent cases are those where clever solutions need to operate. This is where SURF gives the best results and the target region to avail communication opportunities.

4.5 Improvements regarding SURF

The channel selection strategy provided by SURF can be further enhanced by considering the primary radio nodes activity pattern. In the previous section, we have pointed out that the intermittent case is the case where clever solutions need to operate. In this regard, we can evaluate the “power” of using other history-based metrics (that try to better infer the

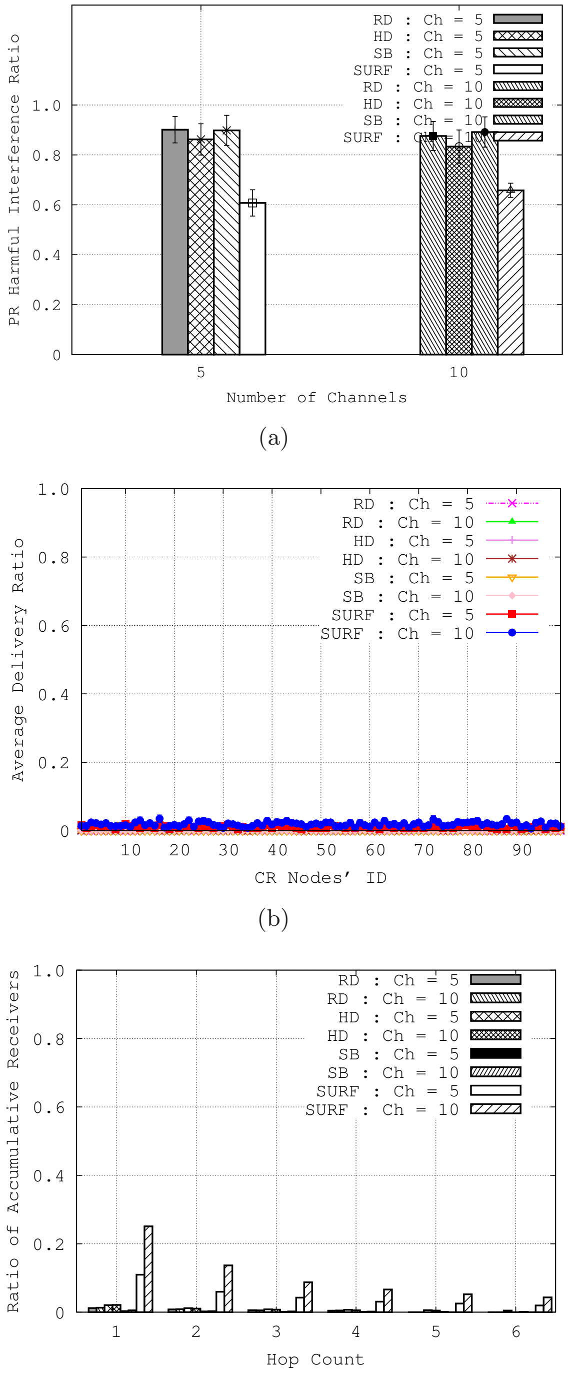


(a)

(b)

(c)

Figure 4.3: Long Term Primary Radio Activity. (a) PR harmful interference ratio for RD, HD, SB and SURF. (b) CR Nodes' ID and average delivery ratio for RD, HD, SB and SURF. (c) Hop count and Ratio of accumulative receivers for RD, HD, SB and SURF.

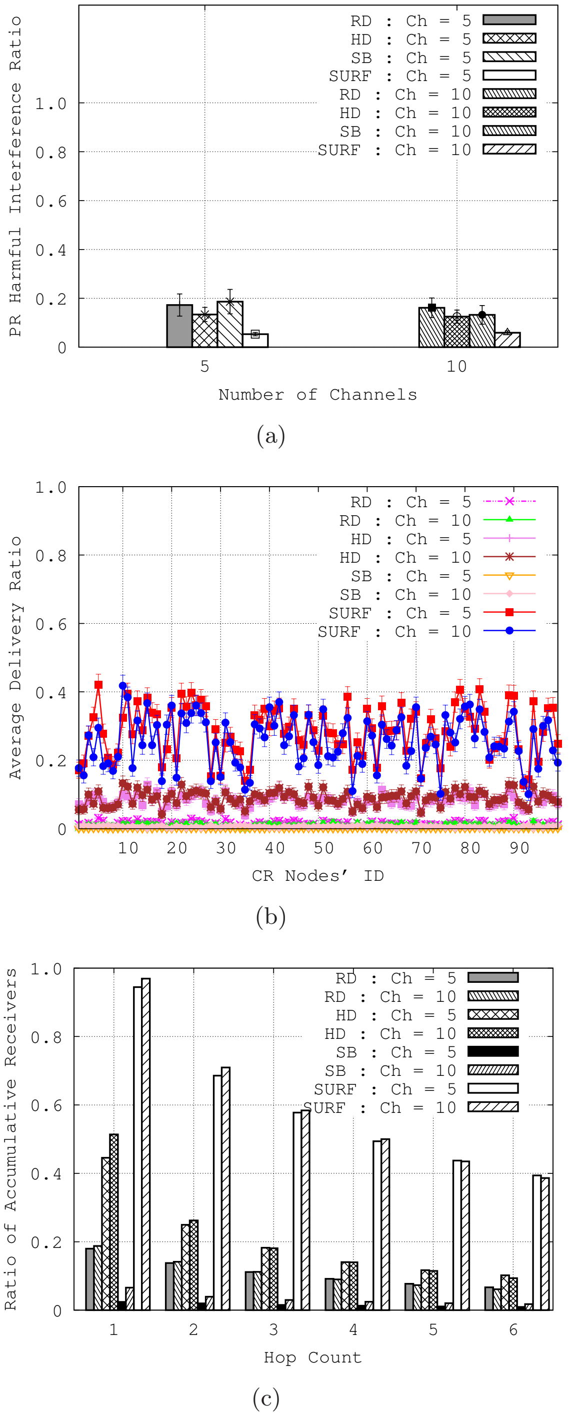


(a)

(b)

(c)

Figure 4.4: High Primary Radio Activity. (a) PR harmful interference ratio for RD, HD, SB and SURF. (b) CR Nodes' ID and average delivery ratio for RD, HD, SB and SURF. (c) Hop count and Ratio of accumulative receivers for RD, HD, SB and SURF.

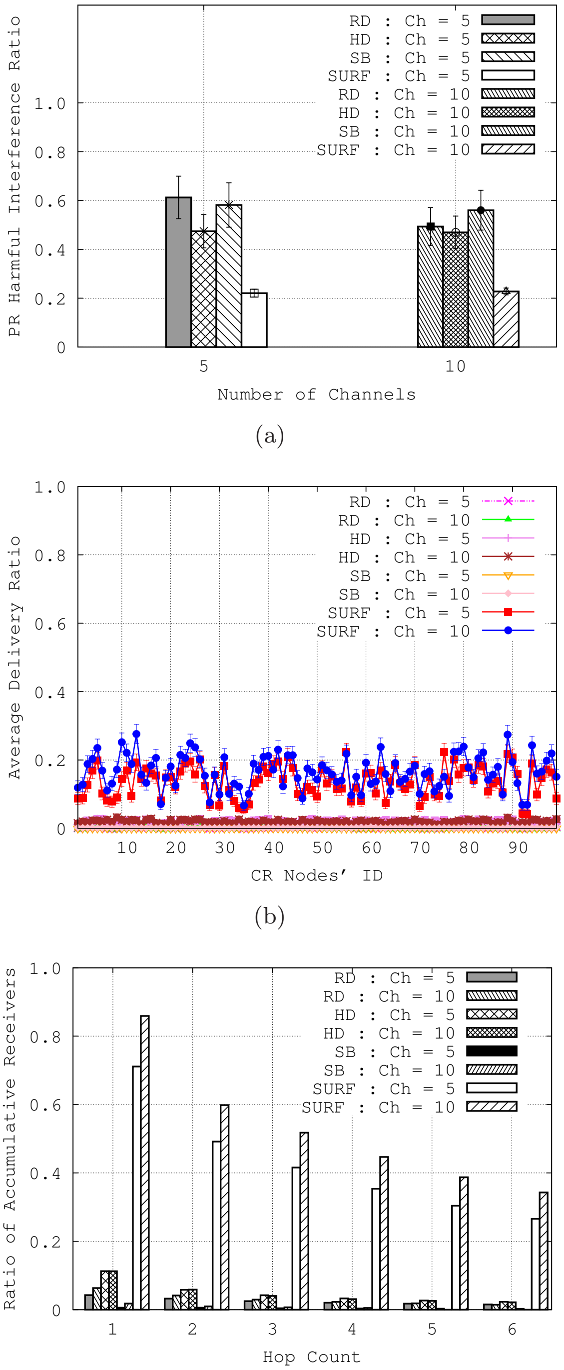


(a)

(b)

(c)

Figure 4.5: Low Primary Radio Activity. (a) PR harmful interference ratio for RD, HD, SB and SURF. (b) CR Nodes' ID and average delivery ratio for RD, HD, SB and SURF. (c) Hop count and Ratio of accumulative receivers for RD, HD, SB and SURF.



(a)

(b)

(c)

Figure 4.6: Intermittent Primary Radio Activity. (a) PR harmful interference ratio for RD, HD, SB and SURF. (b) CR Nodes' ID and average delivery ratio for RD, HD, SB and SURF. (c) Hop count and Ratio of accumulative receivers for RD, HD, SB and SURF.

quality of channels) combined with the current P_w of SURF. SURF is then required to keep track of history of past PR nodes activity. This history could be used to give more weight to the channels with short ON in average. Some examples of metrics are given below:

1) *How often the channel is free?* Here, SURF may keep history of channel ON/OFF states. SURF will consider an "observation time window". The observation time window is defined as the duration of time during which the channel ON/OFF states are observed. In this manner, SURF will compute the ratio of being free over the time window (the size of the time window could be varied to evaluate the impact of ON/OFF states).

2) *How long channels stay in OFF state?* Here, SURF may compute the duration of OFF state over the total time of window size, in the considered time window. This metric depends on how SURF keeps the history of channel states. This could be done on per time slot basis or combining two or more time slots.

3) *What was the ratio of success (reception or transmission) over the times the channel was in OFF state?* This metric will give the quality of the channel in terms of contention. By using this metric, SURF may avoid those channels that are quality wise poor.

Note that all the aforementioned three metrics depend upon when the verification for a free channel is performed (periodically or only when a packet event reception or transmission happens.) Also note that we have not implemented these improvements in SURF and we discuss them in our future work (cf. section 6.2).

4.6 Conclusion and Future Work

In this chapter, we studied the impact of primary radio nodes activity on four channel selection strategies i.e. RD, HD, SB, and SURF. To achieve this, we performed extensive NS-2 simulations. We observed that the channel selection strategies are greatly influenced by the primary radio nodes activity. More particularly, our channel selection strategy SURF outperformed RD, HD, and SB in terms of delivery ratio and causes less harmful interference to PR nodes, in all primary radio nodes activity pattern.

In the following chapter, we will discuss the applicability and feasibility of SURF in two different scenarios. First, we will discuss our proposed cognitive radio based Internet access framework for disaster response networks. We will discuss the architectural details and the working principle of the proposed framework. We will highlight the challenges and issues related with the deployment and connectivity of the framework. Second, we will discuss the applicability of SURF in the context of channel bonding and in this regard, we will discuss an interference based channel bonding strategy for cognitive radio networks.

Chapter 5

Applicability of SURF

Contents

In the previous chapter, we have discussed the impact of primary radio nodes activity on channel selection strategies. We now go one step further and consider two application scenarios and discuss the applicability and feasibility of SURF. In this regard, we first present hereafter a cognitive radio based Internet access framework for disaster response network deployment in challenged environments. Second, we discuss an interference based channel bonding strategy for cognitive radio networks.

The remainder of this chapter is organized as follows: We first discuss the applicability of SURF in disaster response networks and in this regard, section 5.1 discusses the general context. Section 5.1.1 discusses the related work. The architecture of the proposed framework is presented in Section 5.1.2. Issues and challenges concerning deployment and connectivity of the proposed framework are discussed in Section 5.1.3. Section 5.1.4

discusses the use of channel selection strategy SURF in conjunction with the proposed architecture. Second, we discuss the applicability of SURF in channel bonding. In this regard, section 5.2.1 discusses system model and assumptions. In section 5.2.2, we discuss the spectrum characterization. Criteria for channel bonding and adjacent channel interference mitigation are discussed in section 5.2.3. Discussion is done in section 5.2.4, and finally, we conclude in Section 5.3.

5.1 1^{st} Application: General Context of Internet Access Framework

Natural disasters like earthquake or storms are unpredictable and rather a frequent phenomenon these days. The collapse of communications infrastructure is a usual effect of disaster. In fact, different types of communication networks could be affected by a disaster. For instance, base stations of cellular networks or sinks in static Wireless Sensor Networks (WSNs) can be broken, damage in the existing WLANs etc. Thus, these partially damaged coexistent networks that were previously deployed are now disconnected and all kind of wireless communication cease to work.

In spite of technological advancements, the instantaneous deployment of a core telecommunication infrastructure, e.g., a set of base stations in the case of cellular networks, is not feasible because of planning and cost. Besides, there is a quick need to help rescue teams or NGOs to facilitate organized help and rehabilitation works. As performed by engineers in Haiti [136], the deployment of WLANs can be a solution. Nevertheless, its deployment incurs a considerable delay. This motivates the need for a rapid ad-hoc network infrastructure deployment. *The goal of this rapidly deployed ad-hoc network infrastructure is to provide connectivity and Internet access to partially destroyed networks and to help the rescue team members, until the telecommunication infrastructure is repaired.* But, these rapidly deployed disaster response networks, which we referred as challenged networks, impose several constraints like intermittent connectivity, delay, high error rates, no end-to-end paths, unreliable links, heterogeneous devices and operating environment, lack of infrastructure, to name a few. In fact, disasters and emergencies are unpredictable, and network deployment should allow rapid and ad-hoc actions, and must be specifically designed to cater the needs of challenged environments.

In this chapter, we propose a Cognitive Radio Based Internet Access Framework for Disaster Response Network Deployment in Challenged Environments. Through our proposed framework and by exploiting the inherent features of cognitive radio technology, the goal of providing robust connectivity and Internet access to partially destroyed networks can be achieved. In this context, to allow CR devices to restore the connectivity of partially destroyed coexistent network as well as providing Internet accessibility, an architectural framework is required, which in turn provides rapid, cost-effective, and robust connectivity. Recently, [8] discussed the use of cognitive radio in public safety systems, while a cognitive agent based approach for post-disaster communication is proposed in [9]. Nevertheless, the connectivity of partially destroyed networks and their access to the global Internet is still an unaddressed topic.

In challenged environments, *Cognitive Radio Ad-Hoc Networks (CRNs) is a promising technology and capable to federate the communication of coexistent networks temporarily.* In fact, several distinguished features of cognitive radio technology make CRN an easy to deploy and flexible solution for challenged environments. These features include for instance the accessibility and flexibility of communication over the whole spectrum band. Another important advantage CRNs offer is the multi-radio capability, which can further be used to control communication overhead.

5.1.1 Related Work

Recent work on the deployments of cognitive radio networks in post-disaster situations include [8] and [9] but they did not consider the connectivity of partially destroyed networks and their connectivity to the global Internet. Another example is the DIMSUMnet [13] architecture, specifically designed for cellular networks, which is based on a centralized regional spectrum broker and does not cater the needs of rapid and ad-hoc network deployments, mostly required in post-disaster situations. Furthermore, this architecture requires significant time in planning and deployment. It also requires strong coordination with the existing infrastructure, instead of opportunistic, distributed, rapid, and un-coordinated deployments, essentially required in challenged environments.

In addition, cognitive radio ad-hoc networks have been widely used in several application scenarios including military and mission-critical networks [3], [4]. Cognitive radio technology can also play an important role in E-health applications [11], [12]. These aforementioned works are not suitable for post-disaster situation and cannot be directly implemented in such scenarios. Consequently, there is a need to exploit inherent features of cognitive radio technology and tailor them to be well operated for disaster response networks.

5.1.2 An Internet Access Framework for Future Cognitive Radio Networks

Internet Access Framework for Future Cognitive Radio Networks is a three-tier architectural framework tailored to implement and deploy real cognitive radio network applications in challenged communication environments. A general overview of our framework is depicted in Fig. 5.1. The building blocks of this architecture are: (1) Cognitive Radio (CR) devices, (2) Cognitive Multi-Radio Mesh Routers (CMR), and (3) Internet Portal Point.

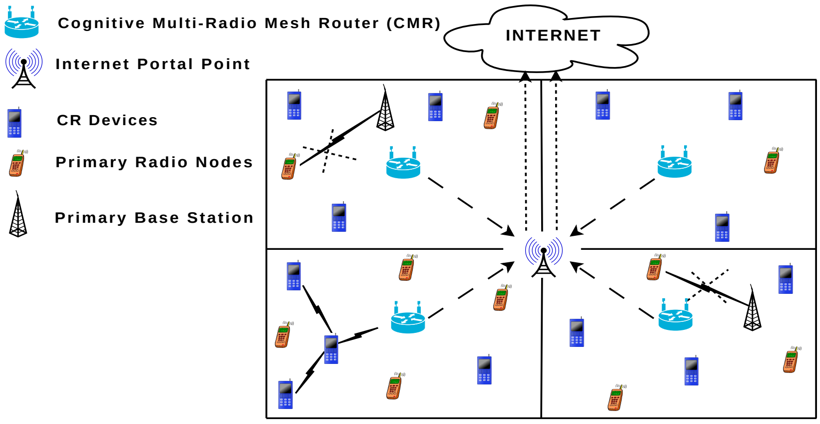


Figure 5.1: An Internet Access Framework for Future Cognitive Radio Networks

In this architecture, we consider partially destroyed networks as primary networks and their nodes as primary nodes. Indeed, our objective is to detect on-going communications of the partially destroyed infrastructures in order to offer them connectivity to other parts of the same infrastructure or even to the Internet. It is clear that interconnecting different type of networks using different technologies can be considered as a challenging task, however, the flexibility and dynamic spectrum management offered by CRN can help to overcome these obstacles. Non-CR devices need to communicate with the CR devices in order to restore their connectivity to other parts of the network and Internet. Practically, when non-CR devices, need to communicate with CR devices, they first need to detect them. To achieve this goal, CR devices can advertise their presence to non-CR devices. Moreover, CR devices have to overhear the channels in order to know if the data transmitted by a non-CR device is for another non-CR device or for a CR device, in order to reach the Internet.

This architecture can be operated in two scenarios: single-hop and multi-hop. CR devices communicate directly with the cognitive multi-radio mesh routers in single-hop scenario, while in multi-hop scenario, CR devices create multi-hop path to reach to the nearest cognitive multi-radio mesh router.

5.1.2.1 Architecture

In Fig. 5.2 we show a practical use case of our framework. In the shown scenario, our architecture acts as a gateway able to federate various existing infrastructures and restore their connectivity to Internet. Hereafter, we describe individually the functionality of the framework components.

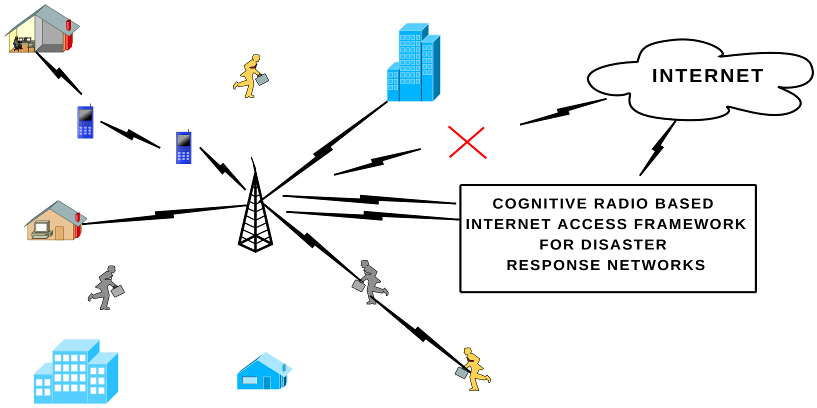


Figure 5.2: A cognitive radio based disaster response network restore the connectivity of partially destroyed network to the global Internet.

Cognitive Radio (CR) Devices Cognitive radio devices which are based on software defined radio can access any cognitive multi-radio mesh router to upload their data to the Internet. These devices can be mobile and are capable of directly communicating with the cognitive multi-radio mesh router in single-hop fashion. They can also create a multi-hop network to reach the nearest cognitive multi-radio mesh router.

In a single-hop scenario, cognitive radio devices are not responsible for their channel selection decision, instead cognitive radio devices will provide feedback to the cognitive multi-radio mesh router about the spectrum occupancy. Cognitive multi-radio mesh router will then make an intelligent decision about channel selection and communicate to CR devices in order to be used for data transmission.

In the multi-hop scenario, the accessibility of CR devices to the CMR is quite challenging due to lack of any centralized authority. Thus, CR devices are responsible themselves to collect the locally inferred spectrum related information and make a channel selection decision alone to reach the cognitive multi-radio mesh router. Therefore, intelligent channel selection techniques should be employed to facilitate CR devices in their channel selection decision.

Basically, cognitive radio devices will be deployed in order to achieve two goals. The first goal is to relay the data of the heterogeneous networks and/or devices to the Internet. The second goal is to provide connectivity to the disjoint networks i.e. non-CR devices. When CRNs are deployed to provide connectivity, CR devices will first perform the discovery of the partially destroyed networks (i.e. infrastructure discovery) and then, tune themselves to the appropriate operating frequency of the disjoint network. In this manner, CR devices will be able to discover still alive non-CR devices. In the meantime, non-CR devices will learn the presence of CR devices in the form of new neighbors. Note that this process will not necessitate any reconfiguration of non-CR devices.

Cognitive Multi-Radio Mesh Routers (CMRs) Cognitive multi-radio mesh routers will be deployed in fixed locations. The main responsibility of these cognitive multi-radio mesh routers is to perform inter-communication between cognitive radio devices and internet portal point to facilitate data transfer and connectivity to the global Internet.

These cognitive multi-radio mesh routers can operate in two scenarios: (1) single-hop, and (2) multi-hop. In the single-hop scenario, cognitive multi-radio mesh routers perform channel monitoring, keep track of the spectrum occupancy, generate spectrum opportunity map [109], and facilitate cognitive radio devices in their reliable channel selection decision. Therefore, in this context, cognitive multi-radio mesh routers are responsible for channel assignment of the CR devices too. In single-hop scenarios, it may happen that non-CR devices generate concurrent transmissions over the spectrum. Thus, cognitive multi-radio mesh routers have to monitor the spectrum, perform sensing to detect free channels, and implement a scheduling algorithm to regulate the transmissions from CR neighbors to cognitive multi-radio mesh routers in such channels, limiting thus the contention. A simple polling mechanism as the one proposed in the IEEE 802.11 standard can be used here to schedule transmissions between CR's and cognitive multi-radio mesh routers. Single-hop scenario can be further classified into standalone approach and coordinated approach, based on the way spectrum opportunities are generated and distributed, as explained hereafter.

In the multi-hop scenario, cognitive multi-radio mesh routers are responsible for data relaying, as well as implementing scheduling algorithm to order the transmissions among their CR neighbors, and to limit contention.

The monitoring of the spectrum and generation of spectrum opportunity map by the cognitive multi-radio mesh routers can be done in two fashions:

- Standalone Approach: In this approach, cognitive multi-radio mesh routers themselves monitor the spectrum fluctuations *without any feedback from or coordination with the CR devices*. Moreover, cognitive multi-radio mesh routers can coordinate with other cognitive multi-radio mesh routers to share spectrum monitoring related information. In this manner, cognitive multi-radio mesh routers maintain a database of the corresponding geographic area and the designated radio spectrum.

- Coordinated Approach: In this approach, cognitive multi-radio mesh routers generate and maintains spectrum opportunity map *by getting the feedback from cognitive radio devices*. These cognitive radio devices that are disperse around the vicinity of cognitive multi-radio mesh routers detect radio spectrum activity and sends this information to the nearest cognitive multi-radio mesh routers. This information contains the channel id, channel utilization time, frequency of the channel, etc.

Internet Portal Point Internet portal point are devices that serves as gateways to the Internet. These devices can be stationary or mobile; equipped with powerful communication medium, e.g., satellite-link. They are responsible for sharing Internet bandwidth to, as well as gathering data from, cognitive multi-radio mesh routers and transfer it to the Internet.

5.1.2.2 Working Principle

Initially the network is deployed having a single internet portal point device. This device should be connected with the global Internet through the satellite link. In the vicinity of this internet portal point, fixed cognitive multi-radio mesh routers are deployed which are directly connected with the internet portal point. Internet portal point shares the Internet connection with these cognitive multi-radio mesh routers. In order to increase the coverage area and provide last-mile connectivity, more cognitive radio devices can be deployed in multi-hop fashion to reach to internet portal point via cognitive multi-radio mesh routers. Then, cognitive radio devices are deployed in such a manner that they co-ordinate with the partially destroyed network nodes and help them to restore their connectivity, or relay their data to the global Internet.

In this manner, the cognitive radio devices first discover the partially destroyed existing infrastructure through spectrum sensing. Once detected, they forward the data of the partially destroyed network to the nearest cognitive multi-radio mesh router. This router further relays the data to the central internet portal point. The data finally reaches the global Internet.

Fig. 5.3 shows different applications of the proposed framework, where the distinct network entities and global Internet connectivity can be restored.

5.1.3 Deployment and Connectivity: Issues and Challenges

In this section, we discuss how the proposed framework addresses the issues and challenges. Note that these issues and challenges are concerning with the deployment and connectivity of the CR devices.

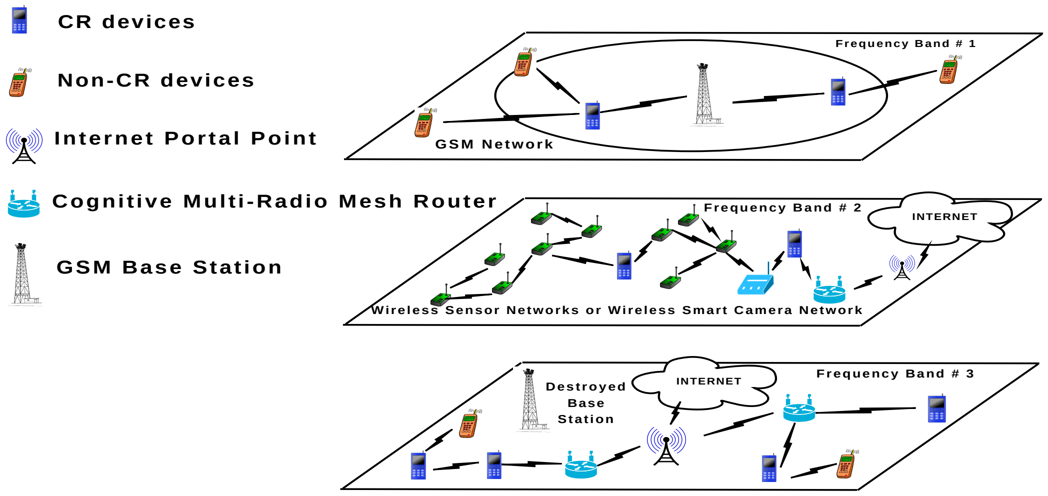


Figure 5.3: Cognitive radio based Internet access framework helps distinct network entities to restore their connectivity to the global Internet.

5.1.3.1 Network Deployment and Connectivity

Depending on the application requirements, the deployment of cognitive radio devices may exhibit different network topologies: (1) single-hop (centralized), and (2) multi-hop (ad-hoc). Besides, traditional self-deployment techniques can add extreme value to the deployment of cognitive radio devices. When the cognitive radio devices are deployed in ad-hoc fashion and they create multi-hop network to reach the cognitive multi-radio mesh router, the main issue is regarding their connectivity. In fact, cognitive radio devices must select reliable channels in order to ensure their connectivity. Otherwise, a CR device that intends to upload its data to the Internet may not be able to find relaying CR devices, and a delay may occur which is undesirable in post-disaster situations. Moreover, without any intelligent channel selection strategy, there will be contention and collisions, resulting in packet losses. Thus, to deal with these issues, we propose to use our channel selection strategy SURF [36] in conjunction with the proposed framework. SURF provides a good level of connectivity and is well suited for these scenarios (cf. Section 5.1.4 for more details).

5.1.3.2 Infrastructure Discovery

Infrastructure discovery is another important aspect that needs to be considered. Primarily due to the deployment of the proposed framework depends on the knowledge of the network that was operating previously. Infrastructure discovery means the identification of the existing infrastructure, such as wireless sensor networks' nodes and sink, Wi-Fi access points, GSM base stations, etc. Insights, such as whether the previously deployed network works with Base Stations (BS) or decentralized mode, with a sink, on which frequency, etc., can aid the initial deployment and configuration of the proposed framework.

In order to restore the connectivity of the partially deployed fixed telecommunication infrastructure like GSM base stations, prior knowledge about the deployed infrastructure is required. This will facilitate to analyze how much CR devices should be deployed and in which geographic region they should be deployed. The real challenge is in restoring the connectivity of networks where prior knowledge of the deployed infrastructure is not available. For instance, WLANs, that operates in the ISM band and can be heavily deployed in urban city regions and office buildings. Thanks to the inherent capabilities of cognitive radio devices e.g., efficient scanning of the radio spectrum, search for beacons or radio signals, and identify the presence of any radio device; the identification of the available communication technology, such as Bluetooth, Wi-Fi, is now possible. Moreover, these techniques can be also used to identify and distinguish different operating devices including Bluetooth piconets, Wi-Fi access points, sensor nodes, and Wi-Fi devices.

5.1.3.3 Inter-network Coordination

Inter-network coordination means how the cognitive radio devices communicate with distinct network entities. This challenge is addressed in the proposed framework by exploiting the inherent capabilities of CR devices. For instance, during the infrastructure discovery phase, CR devices are already being aware of distinct network entities and their operating frequency. A CR device who wants to communicate with a distinct network entity, e.g., a sensor node, tunes itself to the sensor nodes' operating frequency. Consequently, cognitive radio devices have to select one channel to communicate with sensors and other channel to communicate with cognitive radio devices or cognitive multi-radio mesh routers.

5.1.4 Channel Selection Strategy SURF for CR Devices and CMRs

When CR devices want to upload their data to the Internet, they are required to communicate with the cognitive multi-radio mesh router over a particular channel. Without any intelligent channel selection strategy, concentration of all the cognitive radio devices over a particular channel could lead to contention and collision problems, which further reduces the connectivity to the global Internet. Thus, channel selection plays a vital role in efficient and reliable data relaying. This data relaying can be performed between the cognitive radio devices and the cognitive multi-radio mesh router; or among the cognitive radio devices, which operates in multi-hop fashion to reach the cognitive multi-radio mesh router.

In scenarios where cognitive multi-radio mesh routers are responsible for channel assignment to CR devices, SURF could be executed by the cognitive multi-radio mesh routers. Here, the mode of communication between the cognitive radio devices and cognitive multi-radio mesh routers is single-hop. There could be some networking scenarios where CR devices can not directly reach to cognitive multi-radio mesh routers to relay the data to the Internet. Thus, CR devices need to create a multi-hop network. In multi-hop network scenario, the task of relaying data to the cognitive multi-radio mesh routers will be much more challenging. In order to reach cognitive multi-radio mesh routers, cognitive radio devices communicate with other cognitive radio devices and create a multi-hop network. And the main challenge is how to select a reliable channel for CR devices. The selection of reliable channel is difficult due to the diversity in the number of available channels and the lack of any centralized authority. Here, SURF could be implemented by CR devices in multi-hop scenario, as channel selection is performed in a distributed way and is based only on information locally inferred by CR devices. Moreover, in post-disaster situations, SURF can further be enhanced by incorporating priorities to urgent messages to help the disaster victims.

We now discuss the applicability of SURF in the context of channel bonding.

5.2 2^{nd} Application: General Context of Channel Bonding

With the advancement in technology and the availability of cheaper devices, bandwidth-hungry wireless devices can be seen around us. These devices require higher bandwidth due to next generation applications such as VoIP, video, and live streaming. As Shanon proved theoretically that the date rate increases linearly with bandwidth but only logarithmically with signal power or SNR. Thus, one approach to deal with bandwidth-hungriness problem is to adapt the channel bandwidth [137] by combining two or more channels, i.e. *channel bonding* [138]. In *channel bonding*, a set of contiguous non-overlapping channels are bonded together to create a single bonded broadband channel. This results in large aggregated bandwidth, increase in the packet transmission rate, and the better satisfaction of the nodes bandwidth requirements.

In traditional wireless networks, channel bonding has been used for load balancing [137], QoS provisioning [139] etc. The current draft version of IEEE 802.11n also discusses channel bonding in both the 2.4GHz and 5GHz spectrum, where two 20MHz channels are bonded into one 40MHz channel to improve transmission rates [140]. However, aforementioned techniques cannot be directly applied to Cognitive Radio Networks (CRNs) due to the constraints imposed by Primary Radio (PR) nodes, such as the time varying primary radio occupancy [1]. Moreover, for successful reception of data packets, the Cognitive

Radio (CR) sender and receiver nodes should bond the same frequency channels. Thus, intelligent channel bonding techniques are required in CRNs that keep into account the PR occupancy, causing less interference to PR nodes, and tuning the CR sender/receiver nodes to the same bonded channels. It is worth noting that in the context of cognitive radio networks (IEEE 802.22 standard), channel bonding is now practical [141].

In cognitive radio networks, when CR nodes transmit on channels that are adjacent to the primary radio bands, it causes harmful interference to PR nodes [112]. For this reason, during channel bonding, the information regarding the adjacent channels' occupancy is crucial in mitigating interference to its adjacent primary radio nodes [142]. This problem is referred to as Adjacent Channel Interference (ACI) problem [143], [91] in traditional wireless networks. Keeping this in mind, the Federal Communication Commission (FCC) in IEEE 802.22 standard has also restricted fixed devices from transmitting on adjacent channels of the i^{th} active channel. Furthermore, in CRNs, the first priority is to protect the PR nodes, therefore, non-overlapping channels will be used for communication. In summary, it is essential, but extremely challenging to consider adjacent channel interference during channel bonding because of time varying PR occupancy.

Unlike previous approaches [65], [117] [144] which did not consider the adjacent channel interference problem, we carefully consider the adjacent-channel interference problem, while performing channel bonding. In addition, we propose that the channel assignment should be done in such a manner that it should consider the PR occupancy on the adjacent channels. More precisely, the main problem we tackle in this context is *how to perform dynamic channel bonding to satisfy the CR nodes' bandwidth requirements, while considering the PR occupancy and adjacent-channel interference.* In this regard, we propose C-BOND, an adjacent-channel based dynamic channel bonding strategy for single-hop cognitive radio networks.

In C-BOND, first the unoccupied channels are characterized into different types based on free adjacent channels. This characterization is done on the analysis of [142], in which the authors classify the available channels based on PR occupancy of its adjacent channels. In the second step, based on the mechanism we propose, channels are bonded to create a higher bandwidth according to these different types. In the final step, bonded channels are assigned to CR nodes for communication. The proposed channel selection strategy is adaptive in nature and well suited for cognitive radio networks.

5.2.1 System Model and Assumptions

We consider single-hop cognitive radio network architecture. In this architecture, cognitive radio access point (AP) is responsible for spectrum monitoring of the PR nodes. Moreover, we assume that the AP is not resource constrained and is equipped with multiple transceivers. The AP performs channel characterization, channel assignment, and communicate the channel switching decision to CR nodes periodically.

There are total N channels in the network. We assume that the multiple sub-channels can be combined to create a single bonded channel. We assume that cognitive radio nodes are equipped with a single transceiver, where a single channel can be assigned by the access point. This single channel is used for transmission or reception by the cognitive radio nodes. Both, the cognitive radio access point and cognitive radio nodes can freely switch to channels. We further assume that CR nodes may have different bandwidth requirements depending upon the application types.

5.2.2 Spectrum Characterization

The general goal of C-BOND is to dynamically bond the channels and satisfy the CR nodes' bandwidth requirements, while considering the PR occupancy and adjacent-channel interference.

In C-BOND, the AP is equipped with highly sophisticated spectrum sensing techniques. The AP continuously monitors N channels and identifies the unoccupied channels. The main responsibility of the AP is the spectrum characterization, which we describe hereafter:

During spectrum characterization, the AP classifies the N channels into occupied and unoccupied ones. The AP then characterizes the unoccupied channels into 2 major subcategories: (1) interior free channels and (2) border free channels. These two sub-categories are on the basis of the location of the i^{th} free channel [142]:

- Interior Free Channel Case: In this case, the i^{th} free channel is any interior free channel, i.e. $i \neq 1$ and $i \neq N$. This results in four different types of channels based upon free adjacent channels, i.e. Type I-1, I-2, I-3, and I-4 (cf. Fig. 5.4).
- Border Free Channel Case: In this case, the i^{th} free channel is not any interior free channel and is located at the border of the spectrum, i.e. $i = 1$ or $i = N$. This results in two different types of channels based upon free adjacent channels, i.e. Type B-1, and B-2 (cf. Fig. 5.5).

Table 5.1 describes each channel type in detail. We divide these six channels types into two sub-categories: (1) bonded channels category and (2) non-bonded channels category. In the bonded channels category, we propose to use channel Type I-1, I-2, I-3 and B-2. While, Type I-4 and B-1 will be treated as non-bonded channels.

After spectrum characterization, the AP will perform the spectrum assignment. The AP assigns bonded channels i.e. Type I-1, I-2, I-3, and B-2 channels to CR nodes that have higher bandwidth requirements, while Type I-4 and Type B-1 channels will be assigned to CR nodes that have lower bandwidth requirements.

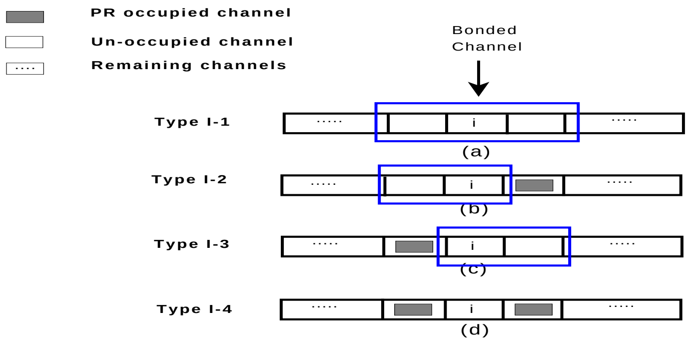


Figure 5.4: Types of channels (Interior Free Channel Case): (a) Type I-1, higher bandwidth category, (b) Type I-2, higher bandwidth category, (c) Type I-3, higher bandwidth category, and (d) Type I-4, lower bandwidth category.

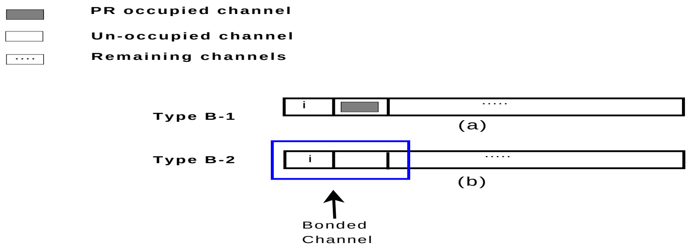


Figure 5.5: Types of channels (Border Free Channel Case): (a) Type B-1, lower bandwidth category, and (b) Type B-2, higher bandwidth category.

5.2.3 Channel Bonding Criteria

We first define the criteria for channel bonding, which is based on the availability of the number of free adjacent channels. This criterion will ensure the AP to mitigate the adjacent channel interference during channel bonding. Type I-1 channel has no adjacent neighbor channels occupied and results in three available contiguous non-overlapping channels. In Type I-1 channel case, the three channels will be bonded to create a single broadband channel. In Type I-2, I-3 and B-2 channel case, two contiguous non-overlapping channels are available. Therefore, these two channels will be bonded to create a single broadband channel. Finally, Type I-4 and Type B-1 channels have their adjacent channels occupied. Thus, in this case, no channel will be bonded and no transmission will be taken place.

We consider the channels of homogeneous bandwidth. A channel i with center frequency $F_{c(i)}$ is shown in Fig. 5.6(a). The bandwidth BW_i of channel i can be written as:

$$BW_i = F_{e(i)} - F_{s(i)} \tag{5.1}$$

Table 5.1: Channel types and their classification.

	Channel Type	Composition	Free Channels
Interior Free Channels	Type I-1 Fig. 5.4(a)	the prior $(i-1)^{th}$ and posterior $(i+1)^{th}$ channels of the i^{th} channel are free.	3
	Type I-2 Fig. 5.4(b)	the posterior $(i+1)^{th}$ channels of the i^{th} channel is occupied by the PR node.	2
	Type I-3 Fig. 5.4(c)	the prior $(i-1)^{th}$ channel of the i^{th} channel is occupied by the PR node.	2
	Type I-4 Fig. 5.4(d)	the prior $(i-1)^{th}$ and posterior $(i+1)^{th}$ channels of the i^{th} channel are both occupied by PR nodes	1
Border Free Channels	Type B-1 Fig. 5.5(a)	the i^{th} channel is at the right or left edge of the spectrum and contains an occupied adjacent channel by PR node in its neighbor.	1
	Type B-2 Fig. 5.5(b)	the i^{th} channel is at the right or left edge of the spectrum and contains a free adjacent channel by PR node in its neighbor.	2

where $F_{s(i)}$, $F_{e(i)}$ are the starting and ending frequencies of channel i. The bandwidth of the channel i from the starting or ending frequency to the center frequency $F_{c(i)}$ can be calculated as:

$$BW_{c(i)} = F_{e(i)} - F_{c(i)} = F_{c(i)} - F_{s(i)} \tag{5.2}$$

where $F_{s(i)}$, $F_{e(i)}$, and $F_{c(i)}$ are the starting, ending and center frequencies of channel i. We now take the case when three channels are combined to create a single bonded channel i.e. Type I channel. The bandwidth of bonded channel i $BW^3_{BC(i)}$ (cf. Fig. 5.6(b)) that bonds the two adjacent channels (i-1) and (i+1) can be calculated as:

$$\begin{aligned} BW^3_{BC(i)} = {} & F_{e(i-1)} - F_{c(i-1)} + GB_{(i-1)\to i} + F_{e(i)} \\ & - F_{s(i)} + GB_{(i)\to(i+1)} + F_{c(i+1)} - F_{s(i+1)} \end{aligned} \tag{5.3}$$

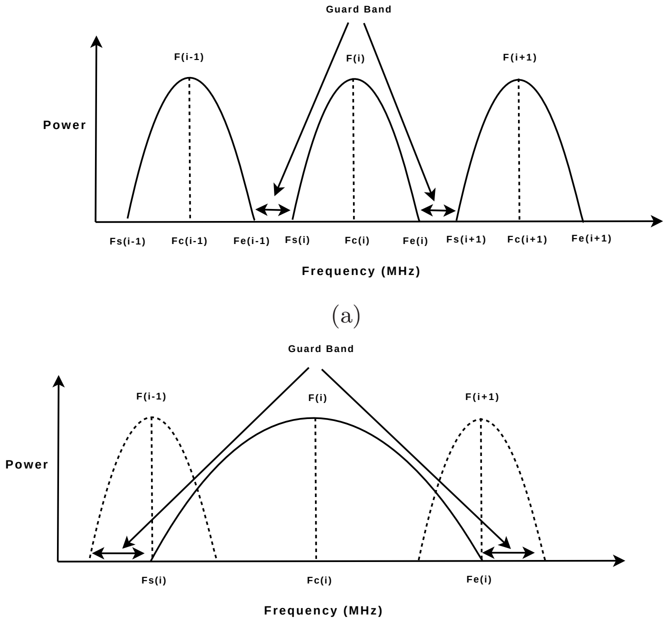
where (i-1) is the prior channel and (i+1) is the posterior channel of channel i. The symbols $F_{s(i)}$, $F_{e(i)}$, and $F_{c(i)}$ are the starting, ending and center frequencies. $GB_{(i-1)\to i}$ is the guard band between channel (i-1) and i and $GB_{(i)\to(i+1)}$ is the guard band between channel i and channel (i+1).

Similarly, the bandwidth of bonded channel i $BW^2_{BC(i)}$ (cf. Fig. 5.7) that bonds one adjacent channel (i+1) can be calculated as:

$$BW^2_{BC(i)} = F_{c(i)} + GB_{(i)\to(i+1)} + F_{c(i+1)} \tag{5.4}$$

where $F_{c(i)}$ and $F_{c(i+1)}$ are the center frequencies of channel i and (i+1), respectively. $GB_{(i)\to(i+1)}$ is the guard band between channel (i) and (i+1).

In order to avoid adjacent channel interference, we adopt a straightforward approach, in which the bandwidth of the bonded channel is increased till the center frequencies of



(a)

(b)

Figure 5.6: An example showing channel bonding (a) when the channels are not bonded and (b) when three channels are bonded to create a single broadband bonded channel.

adjacent channel $(i - 1)$ and $(i + 1)$ (cf. Fig. 5.6(b)) and the bandwidth is expressed in Eq. 5.3. We adopted this approach primarily because a large guard band is required at the band edges when performing channel bonding [141]. It is worth mentioning here that the guard band in between channels can be reused through channel bonding.

5.2.4 Discussion

Our channel bonding strategy C-BOND has some clear advantages, such as it supports dynamic channel bonding but also considers the adjacent channel interference. This results in minimum interference with PR nodes. In C-BOND, CR nodes are required to equip with a single transceiver and thus reduces the operational cost of the network. Moreover, the bandwidth is assigned to CR nodes according to their traffic requirements. In this manner, higher capacity gains could be achieved by sending packets with higher data rates.

Besides these advantages, there are some challenges that we need to investigate in detail.

1. *How often the channel assignment is triggered?* In traditional wireless networks, the channel assignment is often triggered when a new node join/leave the AP or a new data flow start by a node. In the context of CRNs, the appearance of primary radio nodes on the assigned channel may lead to trigger the channel assignment again. The

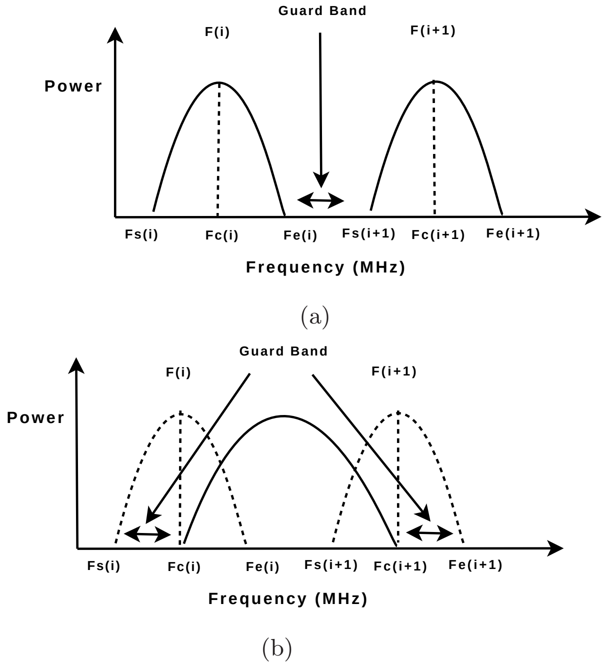


Figure 5.7: An example showing channel bonding (a) when the channels are not bonded and (b) when two channels are bonded to create a single broadband bonded channel.

channel assignment will become more frequent in the case of channel bonding, as the probability of PR appearing nodes increases with the number of used channels during channel bonding. The triggering of channel assignment can be minimized by predicting the PR activity.

2. *How to select stable free channels during channel bonding?* This means, PR nodes can re-appear on the bonded channel. Consequently, the bonded channel is broken and given back to PR nodes for transmission. The question is, how the transmission should be handed over seamlessly to another bonded channel with the same bandwidth size. One approach to deal with this problem is to maintain a pool of bonded channels at the AP. This pool contains the list of most probable channels for channel bonding with respect to their sizes. E.g., when a bonded channel with 2 sub-channels is broken then the AP select and assigns the next bonded channel of the same size to the CR node.

   Note that, if the pool of the bonded channels is already being used by the neighboring CR nodes and no free bonded channel is available, then CR node may use the non-bonded available channel for communication. However, this will reduce the data rate of the CR node.

3. *How to achieve maximum capacity gain while causing less interference to PR nodes?* In C-BOND strategy, we suggested to increase the bandwidth till the center frequency of the adjacent channels. Although, this ensures significant reduction in PR interference but there would be some capacity losses.

   In order to achieve maximum capacity gain while causing less interference to PR nodes, we have to consider *the tradeoff between the channel separation distance and PR interference.* If the channel separation distance is small, PR may get interference, while if it is larger, capacity loss will be there. Thus, we need to quantify this tradeoff through simulations.

4. *How many channels can be used for Bonding?* One may think to bond as many channels for transmission but there exists a tradeoff; *the higher the number of bonded channels, the higher is the probability of being interrupted by PR transmissions.* Thus, one approach is to consider channels with longest remaining idle time for channel bonding.

5. *Which type of channels to be used for channel bonding?* In cognitive radio networks, the available channels can be categorized into three types: (1) Overlapping, (2) Non-overlapping, and (3) Partially overlapping. The first priority in CRNs is to protect the PR nodes, therefore, overlapping and partially overlapping channels cannot be used for channel bonding. The only candidate for channel bonding in CRNs is non-overlapping channels. However, the challenge resides in finding the consecutive non-overlapping *idle* channels.

6. *How interference can be handled?* In CRNs, interference can be caused between: (1) CR-CR nodes, (2) CR-PR nodes, and (3) AP-AP. The interference between CR nodes can be caused when the AP assigned the channel to the CR node whose i^{th} active channel is already being used by another CR node. The CR-PR interference can be caused when a channel is assigned to CR node whose i^{th} active channel is already being used by PR node. While, inter-AP interference can be caused if the same channel is assigned to the neighboring AP. All these three types of interference can be handled by employing an intelligent channel assignment on the AP. For instance, one way to reduce the CR-PR interference by the AP is to select those channels that have longest remaining idle time.

7. *How to deal with CR occupancy?* During channel assignment, besides PR occupancy, the AP also requires to consider the CR occupancy on the adjacent channels. Otherwise, the CR nodes cause harmful interference among each other, which may degrade

the performance of CR nodes. In order to deal with CR occupancy, the AP can assign those channels to CR nodes which are non-consecutive.

How SURF can be used with C-BOND? We now discuss how SURF could be used in conjunction with C-BOND. In fact, stable free channels can only be selected if the primary radio activity is considered during the channel selection. As shown in section 3.7.1, SURF specially considers the PR activity during channel selection decision and causes very less harmful interference to primary radio nodes. Thus, SURF can be used to select stable channels.

5.3 Conclusion

In this chapter, we have proposed a generic framework that enables partially destroyed networks to first restore their connectivity locally and also to connect to the Internet. The originality in our proposal resides in exploiting inherent properties of CRNs, such as dynamic channel switching and channel sensing to tune to the frequency bands exploited by destroyed infrastructure replace spoiled equipment. Our architecture is specially designed to cater the needs of challenged environments. We have also highlighted issues and challenges in the deployment of this architecture. We believe that this work can serve as a basis to build new algorithms and protocols for CRN that can federate heterogeneous networks and communications technologies in challenged environments. We mentioned that in this framework, SURF could be used by CR devices and CMRs.

Furthermore, we also discussed the applicability of SURF in the context of channel bonding. In this context, we proposed C-BOND, a dynamic channel bonding strategy, specifically designed for single-hop cognitive radio networks. C-BOND is designed in such a way that it satisfies the CR nodes' bandwidth requirements, while considering the PR occupancy and adjacent-channel interference. We discussed that SURF could be used in conjunction with C-BOND to select stable channels in terms of PR activity.

We now move towards the conclusion and future work in the following chapter.

Chapter 6

Conclusion and Future Work

Contents

In this thesis, we have proposed a channel selection strategy, SURF, for data dissemination in infrastructureless multi-hop cognitive radio ad-hoc networks. In addition, we studied and analyzed the impact of PR nodes activity patterns on different channel selection strategies. We have also discussed the applicability and feasibility of SURF.

Moreover, during this thesis, we learnt that the primary radio activity model plays a vital role in the performance of cognitive radio network. Thus, it is necessary to consider a good primary radio activity model that captures well the activities of PR nodes. Similarly, CR neighbors and collision should be well considered. We stress that the design of new channel selection strategies should consider PR activity, CR neighbors and collision. We also observed that validating channel selection strategies in home-made simulators can not well characterize the behaviour of channel selection strategies. This is because home-made simulator does not provide the real propagation and link-access conditions. Thus, we stress that more realistic simulators should be used to validate the channel selection strategies. We now provide the summary of our contributions.

6.1 Summary of Contributions

Data dissemination in cognitive radio networks brings several challenges. We first highlighted those challenges in detail. We then argued that the first step in having efficient and robust data dissemination is to select the best channel. We then mentioned some key required characteristics of any channel selection strategy for data dissemination in cognitive radio networks. Several channel selection strategies have been proposed for cognitive radio networks in the literature. We performed an extensive literature review on channel selection strategies and classified those channel selection strategies according to their goals, nature, and communication perspective.

The main contribution of this thesis is SURF, a channel selection strategy for data dissemination in multi-hop cognitive radio networks. In SURF, the objective of every cognitive radio node is to select the best channel ensuring a maximum connectivity and consequently, allowing the largest data dissemination reachability in the network. This corresponds to the use of channels having low primary radio nodes (PRs) activities, as well as having higher number of CR neighbors.

The classification of channels in SURF is done on the basis of primary radio unoccupancy and the number of cognitive radio neighbors using the channels. Another main challenge we dealt in this thesis was residing in making efficient and reliable channel selection decisions on-the-fly and in recovering from bad channel selection decisions. To deal with this challenge, we introduced the mechanism of recovery from bad channel selection decision. In this mechanism, SURF keeps track of previous wrong channel state prediction and accordingly adapts future channel selection decision. Usually channel selection strategies provide a way to nodes to select channels for transmission. Besides, SURF endues CR nodes to select best channels also for overhearing. This helped to tune both sender and receiver with high probability to the same channel. As a consequence, SURF may have high number of neighbors on the selected channel. In addition to that, SURF protects the PR nodes by considering the PR unoccupancy in channel selection decision, for effective and robust data dissemination.

To validate SURF, we used Network Simulator NS-2 for our simulation-based studies. NS-2 has been widely used in the wireless networking research. Nevertheless, due to the fact that research in CRNs is very recent, a complete and accurate simulation module for CRNs in NS-2 was not still available. In order to deal with such lack, we modified the NS-2 and added missed CRNs functionalities. We used the Cognitive Radio Cognitive Network (CRCN) patch of NS-2. This CRCN patch of NS-2 does not support the activity of the PR nodes. Thus, we enhanced the CRCN patch of NS-2 to include the PR activity model. Moreover, we also modified the MAC protocol to incorporate the PR activity model in

NS-2.

We studied the impact of primary radio nodes activity on four channel selection strategies i.e. RD, HD, SB, and SURF. We observed that the channel selection strategies are greatly influenced by the primary radio nodes activity. More particularly, our channel selection strategy SURF outperformed RD, HD, and SB in terms of delivery ratio and causes less harmful interference to PR nodes, in all primary radio nodes activity pattern.

Finally, in this thesis, we discussed the applicability and feasibility of SURF. In this perspective, a cognitive radio based Internet access framework for disaster response networks has been proposed. We discussed the architectural details and the working principle of the proposed framework. We highlighted the challenges and issues related with the deployment and connectivity of the framework. We then discussed the applicability of SURF in the context of channel bonding and in this regard, we discussed an interference based channel bonding strategy for cognitive radio networks.

6.2 Future Research

We conclude our thesis by mentioning some of the future research directions.

6.2.1 Channel Activity Models of a PR Network

With the advancement of technology, several wireless network models and standards have been proposed. Some famous wireless networks are IEEE 802.11 based networks, 3G Mobile Networks, WiMax networks, ZibBee etc. However, the activity of primary radio nodes varies from network to network. Due to this varying PR activity and non-conformity in the wireless standards, a single primary radio activity model cannot captures the activity of primary radio nodes accurately. Thus, several channel activity models of PR networks has been proposed in the literature, e.g., Bernoulli Process, Deterministic Process, General Distribution, and Beta Distribution. One interesting direction is to develop adaptive strategies that could able to detect the PR activity. In addition, if more sophisticated spectrum sensing algorithms are used in conjunction with channel selection strategies, they may help to enhance the performance of cognitive radio networks' performance.

6.2.2 Exploitation of Real Traces of PR Activity

The importance of considering real traces of PR activity cannot be ignored. But the main challenge one can face is the availability of PR activity traces. In the literature, although studies have been done to measure the large scale PR activities but the traces are not available publicly. For instance, authors in [145] has conducted the study on large scale measurements of PR nodes in cellular networks but these traces are proprietary and are not available publicly. As a consequence, most of the research in CRNs is dependent on the accuracy of mathematical models and there is a need to exploit real PR activity traces to minimize the gap between theory and practice.

6.2.3 Improvements in SURF considering PR activities' study

SURF channel selection strategy can be further enhanced by considering the primary radio nodes activity pattern. As we have pointed out in this thesis that the intermittent primary radio activity case is the case where clever solutions need to operate. In this regard, we can incorporate other history-based metrics (that try to better infer the quality of channels) combined with the current P_w of SURF. One example could be: *How often the channel is free?* Here, SURF may keep history of channel ON/OFF states. SURF will consider an "observation time window". The observation time window is defined as the duration of time during which the channel ON/OFF states are observed. In this manner, SURF will compute the ratio of being free over the time window (the size of the time window could be varied to evaluate the impact of ON/OFF states). In addition, we can also consider *How long channels stay in OFF state?* Here, SURF may compute the duration of OFF state over the total time of window size, in the considered time window. This metric depends on how SURF keeps the history of channel states. This could be done on per time slot basis or combining tow or more time slots. Finally, in SURF, we can consider *What was the ratio of success (reception or transmission) over the times the channel was in OFF state?* This metric will give the quality of the channel in terms of contention. By using this metric, SURF may avoid those channels that are quality wise poor.

6.2.4 Channel Bonding in Cognitive Radio Networks

In SURF, we can incorporate another important aspect that could be exploited in the context of cognitive radio networks for efficient and robust communication. In fact, we could exploit the availability of contiguous non-overlapping channels to create a bonded channel and use it with our channel selection strategy.

Through channel bonding [141,146,147], multiple frequency channels are bonded into a single broadband channel. Therefore, the aggregated bandwidth is larger due to the sum of multiple frequency channels and as a consequence, the rate of packet transmission increases. This will also reduce the packet transmission time. Another advantage of channel bonding is the low delay. In other words, the use of channel bonding in conjunction with our channel selection strategy SURF, allows CR users to efficiently disseminate and share information. In future, we intend to characterize the number of channels to be bonded and its impact over network performance metrics.

6.2.5 Spontaneous CR deployments

Spontaneous CR deployments are another important aspect that could be deal in future. In fact, the goal of this rapidly deployed ad-hoc network infrastructure is to provide connectivity and Internet access to partially destroyed networks and to help the rescue team members, until the telecommunication infrastructure is repaired. But, these rapidly deployed disaster response networks, which we referred as challenged networks, impose several constraints like intermittent connectivity, delay, high error rates, no end-to-end paths, unreliable links, heterogeneous devices and operating environment, lack of infrastructure, to name a few. All these constraints should be considered in future spontaneous CR deployments.

Appendix A

Thesis Publications

Journal

- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *SURF: A Distributed Channel Selection Strategy for Data Dissemination in Multi-Hop Cognitive Radio Networks*, **Submitted to: Computer Communications Elsevier Journal**, May 2011.

International Conferences

- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *Activity Pattern Impact of Primary Radio Nodes on Channel Selection Strategies*, In Proceedings of the 4th International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART'11), in conjunction with ISABEL 2011, Barcelona, Catalonia, Spain, 26- 29 Oct 2011.
- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *Improving Data Dissemination in Multi-Hop Cognitive Radio Ad-Hoc Networks*, 3rd International ICST Conference on Ad Hoc Networks (ADHOCNETS 2011), 21-23 Sep 2011, Paris, France. Published in the Proceedings of Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering (LNICST), Springer.
- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *A Cognitive Radio Based Internet Access Framework for Disaster Response Network Deployment*, In Proceedings of the 3rd International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART'10), in conjunction with ISABEL 2010, Rome, Italy, 08- 10 Nov 2010.
- Mubashir Husain Rehmani, *Channel Assortment Strategy for Reliable Communication in Multi-Hop Cognitive Radio Networks*, In Proceedings of the 11th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM 2010), Extended Abstract, Montreal, QC, Canada, June 2010.

National Conference

- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *Adaptive and Occupancy-based Channel Selection for unreliable Cognitive Radio Networks*, Rencontres Francophones sur les Aspects Algorithmiques des Telecommunications (ALGOTEL) 2009, du 16 au 19 juin 2009, Carry Le Rouet, France.

Technical Reports

- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, SURF: A Distributed Channel Selection Strategy for Data Dissemination in Multi-Hop Cognitive Radio Networks,, INRIA Research Report RR-7628, May 2011.http://hal.inria.fr/inria-00596224/en/
- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, A Cognitive Radio Based Internet Access Framework for Disaster Response Network Deployment, INRIA Research Report RR-7285, May 2010. http://hal.inria.fr/inria-00482593/en/
- Mubashir Husain Rehmani, Aline Carneiro Viana, Hicham Khalife, and Serge Fdida, *Toward Reliable Contention-aware Data Dissemination in Multi-hop Cognitive Radio Ad Hoc Networks*, INRIA RR-0375, 2009, France. http://hal.inria.fr/inria-00441892/en/.

Appendix B

NS-2 Contributed Code

Contents

B.1 NS-2 Modifications

We used CRCN patch of NS-2. This CRCN patch of NS-2 does not model the activity of the PR nodes. Thus, we enhance the CRCN patch of NS-2 to include the PR activity model. The NS-2 code can be downloaded from here [148]. The PR activity block is responsible for generating and keeping track of PR activities in each spectrum band (spectrum utilization) i.e., sequence of ON and OFF periods by PR nodes over the simulation time. These ON and OFF periods can be modelled as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [116], [118]. The ON (busy) state means the channel is occupied by the PR node. While, the OFF (idle) state means the channel is unoccupied by the PR node. We consider the channels ON and OFF periods are both exponentially distributed, as in [118], [119]. The rate parameter λ_X and λ_Y (cf. Table 3.1) of the exponential distribution is provided as an input in the simulation, which were measured by authors in [119]. Then, according to this rate parameter, channels follow the ON and OFF periods.

We achieve this by binding the variables in the TCL script with the C++ code of NS-2 and by using timers of NS-2. As soon as channels are declared in the TCL script and simulation begins, each channel undergoes ON and OFF states throughout the simulation period.

First, we define the variables:

```
set val(channum) 8 ;# number of channels per radio
set val(acschan) 5 ;# number of available channel set (acs) channels
```

Now, we access the handle for the MAC layer in the tcl script by the following statement:

```
set Mub_Mac_(0) [$node_(0) set mac_(0)]
$ns_ at 0.00 “$Mub_Mac_(0) board $val(channum) $val(acschan)”;
```

In the Command of the MAC layer, we deal the “board” as follows:

```
int MubashirMac::command(int argc, const char*const* argv) {
if (argc == 3) {
..........
return TCL_OK;
}
}
else if (argc == 4) {
if (strcmp(argv[1], “board”) == 0) {
We call here the function that call the timer.
return TCL_OK;
}
}
return Mac::command(argc, argv);
}
```

In NS-2, timers are used to delay actions or they can be used for the repetition of a particular action like broadcasting of Hello packets after fixed time interval. We used timers to simulate channels ON/OFF states. The timer is declared int the macmubashir.h file.

```
/ / Timer for channel activity – channel # 1
class ChannelOccupancy_Timer : public TimerHandler {
public:
ChannelOccupancy_Timer(MubashirMac *a) : TimerHandler() { a_ = a;}
void expire(Event *e);
protected:
```

```
MubashirMac *a_;
};
```

We futher declare the ChannelOccupancy_Timer as a friend class of MubashirMac as:

```
class MubashirMac : public Mac {
friend class ChannelOccupancy_Timer;
public:
ChannelOccupancy_Timer ChannelOccupancy_Timer_;
}
```

We consider a simple mac protocol (Maccon.cc), available with the CRCN patch of NS-2. This mac protocol is a multiple-channel, collision and contention-based mac protocol. Note that in the original state, the Maccon.cc mac protocol selects channel randomly from the predefined set of channels and the channel selection decision occurs at the mac layer. We now perform channel selection at the network layer. Thus, we modify this mac protocol and provide the capability to the network layer to make the channel selection decision. We further add channel selection strategies RD, HD, SB and SURF to the network layer, which we describe hereafter. Based upon any particular channel selection strategy, the network layer takes the channel selection decision. This channel selection decision is encapsulated in the network layer packet header and it is passed to the mac layer, which then switch to the channel based on the channel selection decision provided by the network layer.

In the Maccon.cc mac protocol, there are two channel states: $IDLE$ and $BUSY$. These states are dependent on the channel conditions and they are used by the mac protocol to handle the transmission and reception activities of CR nodes. $IDLE$ means that the no activity is going on on the channel and the channel is free to use for transmission by the CR node and $BUSY$ means that the channel is occupied by any undergoing CR transmission. In order to deal with the activities of the PR nodes, we include for each channel two more states at mac layer i.e., $PR\_OCCUPIED$ and $PR\_UNOCCUPIED$, indicating that the channel is occupied and unoccupied by the PR node, respectively. These two states of the channel will be checked each time by the mac protocol while performing transmission or overhearing.

Appendix C

Version Française

Contents

Les récentes avancées dans les technologies de la communication et la prolifération de l'informatique sans fil et des dispositifs de communication surpeuplent le spectre radio. Dans cette perspective, beaucoup de travaux ont été effectué pour améliorer l'utilisation du spectre au cours des derniéres décennies. Cela comprend l'utilisation de technologies d'accés différentes, par exemple, Frequency Division Multiplexing (FDM), Time Division

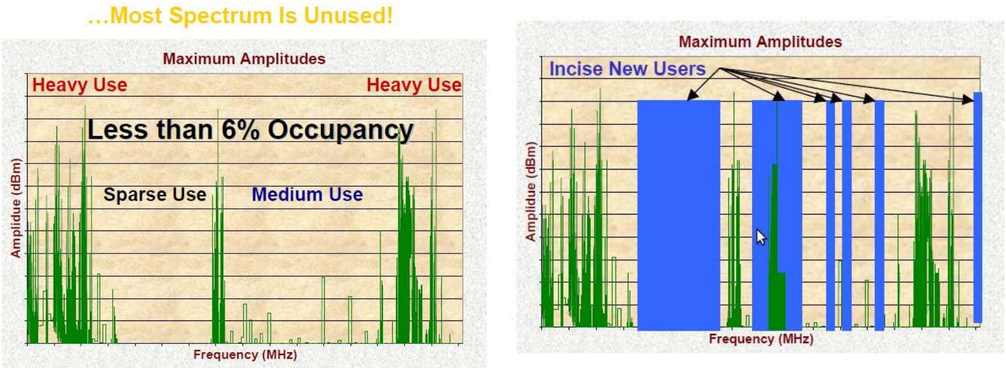
Multiplexing (TDM), Code Division Multiple Access (CDMA), et Orthogonal Frequency Division Multiple Access (OFDMA). Du point de vue de la configuration du réseau, le spectre radio électrique est géographiquement réutilisé pour surmonter la rareté du spectre, par exemple, micro, pico et femto cellules de Global System for Mobile Communications (GSM). Cependant, les expériences de la Federal Communication Commission (FCC) révélent que l'utilisation du spectre varie encore de 15 % -85 % avec fréquence, temps et localisation géographique (e.g., Fig. C.1 pris par [1], [2]). Exigeant ainsi la nécessité d'utiliser le spectre radio opportuniste a travers la technologie radio cognitive (CR).

La technologie radio cognitive a ouvert de nouvelles portes pour les applications émergentes. La radio cognitive peut être utilisée dans les réseaux Smart Grid, réseaux de sécurité publique, après la catastrophe [8], [9] et réseaux sans fil médicale [10], [11], [12]. Dans les situations d'urgence, avec l'aide de multi-interfaces ou radio réalisée par logiciel (SDR), les nœuds CR peuvent servir pour faciliter la communication pour d'autres appareils qui peuvent fonctionner dans différentes bandes et / ou ont des interfaces sans fil incompatibles. La technologie de réseaux cognitifs peut également être utilisée pour fournir un accès opportuniste de grandes parties du spectre sous-utilisé dans les réseaux cellulaires [13]. En plus, la technologie de réseaux cognitif a été largement utilisé dans les scénarios d'application de plusieurs réseaux, y compris militaire et mission critique [3], [4], et des applications basées sur le consommateur [5], [6], [7]. La technologie de réseaux cognitif pourrait être très utilisées pour les communications de données fiables et en temps opportun pour accéder des nuages (clouds) [149].

La technologie radio cognitive peut aider les réseaux tolérants au délai (DTNs) pour fournir des informations fiables, sensibles au retard des possibilités de communication [14]. En application les technologies DTNs et CR pourraient très utilisées dans le scénario urbains à forte densité de dispositifs sans fil provoquant un retard dans la communication en raison de discorde sur le lien. Les Radios cognitives ainsi aident à trouver des canaux vides pour une utilisation opportuniste et assurent la livraison des messages.

Les réseaux de capteurs sans fil (WSN) est un autre domaine où la technologie de radio cognitive pourrait très utilisée soit en fournissant une connectivité Internet à l'évier ou aider à relier les parties disjointes des réseaux. Par ailleurs, la technologie de radio cognitive peut atténuer les problèmes de discorde, les collisions et les pertes de paquets dans une certaine mesure sur la bande ISM de surpeuplement extrême en offrant plus d'espace de communication aux dispositifs de capteurs et donc, améliore l'utilisation du spectre global.

Même l'utilisation opportuniste de plusieurs canaux en utilisant la capacité de la radio cognitive dans les nœuds de capteurs sans fil peut être très utile dans le cas de réseaux de capteurs multiples déployées au cours de la meême région pour la surveillance de différents événements [15]. Dans ce contexte, beaucoup de travaux ont été fait sur les défis de conception principaux, domaines d'application, l'efficacité énergétique [16], l'amélioration de la durée de vie du réseau [17], le canal et la puissance distribuée régimes d'attribution [18] et les architectures de réseau de prospective des réseaux de capteur radio cognitifs [19], [20], [21], [22]. Nous allons maintenant décrire les réseaux radio cognitifs.



(a) (b)

Figure C.1: La spectrum est gaspillée. L'accès au spectre opportunistes peuvent apporter des améliorations dans l'utilisation du spectre.

C.1 Réseaux Radio Cognitifs

Les réseaux de radio cognitive sont composées d'appareils de radio cognitive. L'article fondateur de J. Mitola [23] introduit le concept de radio cognitive. Ian F. Akyildiz et al. [1] définit la radio cognitive comme:

" la "radio cognitive" est une radio qui peut changer les paramétres du transmetteur basé sur l'interaction avec l'environnement dans lequel elle opére".

La motivation derriére la radio cognitive est triple: (1) la disponibilité du spectre limité, (2) la politique de l'assignation des fréquences fixes, et (3) l'inefficacité dans l'utilisation du spectre. Par conséquent, les réseaux de radio cognitive sont connus pour exploiter de façon opportuniste le spectre sous-utilisé. Par ailleurs, les organismes de réglementation, tels que, la Federal Communication Commission (FCC) [24] ont également promu l'idée d'utiliser les appareils de radio cognitive pour répondre au probléme de pénurie de spectre. Dans cet égard, la FCC a connu une politique opportuniste d'accés au spectre sans interférence [24]. Selon la politique de la FCC [24], les canaux ne sont autorisés à être utilisé que par les nœuds radio cognitifs (CR) i.e., pas utilisé par les nœuds de radio primaire (PR) et pour les nœuds PR [1], [25]. En fait, les nœuds PR sont les utilisateurs existants et ils ont une priorité plus élevée à utiliser la bande sous licence. Afin de se conformer à la politique de la FCC, les nœuds CR devraient éviter de causer des interférences nuisibles aux nœuds de PR. Les nœuds CR peuvent profiter des canaux de ralenti pour diffuser des messages non urgents et la publicité à faible coût et complexité.

C.1.1 Architecture

Selon l'architecture du réseau, il existe deux principaux types de réseaux, l'un est le réseau primaire et le second est le réseau radio cognitif. Le réseau primaire est toute infrastructure existante qui a un droit exclusif pour accéder à une certaine bande de fréquences. Les exemples de réseaux primaires sont les réseaux de diffusion TV et les réseaux cellulaires. Un réseau primaire est composé de nœuds radio primaires. Le réseau radio cognitif peut être classé comme celui *fondé sur les infrastructures* et *sans infrastructure* . Les sans infrastructure peuvent aussi être appelés réseaux radio cognitifs Ad-Hoc (CRN) [26] .

Le réseau d'infrastructure à base de radio cognitive est une entité du réseau central, comme un point d'accés dans les réseaux locaux sans fil (LAN) ou une station de base dans les réseaux cellulaires. Alors que dans le réseau radio cognitif sans infrastructure, aucune entité centrale n'est présente pour faciliter les nœuds de communication CR.

Les réseaux radio cognitifs à infrastructures sont des réseaux dans lesquels un courtier spectre est responsable de la détection du spectre, l'affectation et la gestion, et les réseaux radio cognitifs sans infrastructure sont des réseaux dans lesquels dans lequel les nœuds CR sont eux-mêmes responsables de la détection du spectre, l'affectation et de la gestion. Le premier n'est pas préférable à la suite car un canal de controle dédié est nécessaire et peut être exposé à des menaces différentes comme Dénie de Service (DoS). *Dans cette thèse, nous nous concentrons sur l'architecture sans infrastructure ou les réseaux ad-hoc radio cognitifs.* Dans les architectures sans infrastructure, les nœuds CR sont responsables de la détection, le partage, la gestion, et la mobilité du spectre [1].

C.2 Problématique

Dans cette thèse, nous nous concentrons sur la diffusion de données dans les réseaux ad-hoc radio cognitifs. La diffusion des données est communément définie comme étant la propagation d'informations à de multiples destinations à travers la radio diffusion. L'objectif principal est d'atteindre le nombre maximum des voisins avec chaque paquet envoyé. Dans ce schéma de communication, aucun routage n'est exigé ainsi ni les tables de routage ni les chemins bout à bout sont maintenus. Parmi différentes applications où la diffusion de données peut être utile, nous nous concentrons dans ce travail sur les scénarios de réseau où les fournisseurs disséminent les messages non-urgents afin de limiter le coût et la complexité dans le réseau, comme : services, mises à jour (par exemple, le nouveau code de recharge d'un service fourni), ou tout genre de message de publicité. Toutefois, garantir la fiabilité des données disséminées dans les réseaux sans fil est une tâche très ardue. En effet, les caractéristiques et les problèmes intrinsèques des liens sans fil ajoutent plusieurs soucis sous forme de pertes de messages, collisions, et problème de tempête de diffusion, pour n'en citer que quelques-uns.

Particulièrement dans le contexte des réseaux radios cognitifs sans fil (CRN) [1], où les fréquences de transmission sont sélectionnées de manière opportuniste, et la fiabilité est difficile à réaliser. Cela est dû aux caractéristiques inhérentes de ces réseaux. Premièrement, en plus des difficultés déjà connues des environnements sans fil, la diversité dans le nombre de fréquences qu'un nœud radio cognitif a le droit d'utiliser ajoute un autre défi, en limitant l'accessibilité à ses nœuds. Deuxièmement, les nœuds radio cognitif (CR) doivent conquérir les ressources de fréquences résiduelles avec les nœuds à radio primaire(PR), tout en essayent de les exploiter d'une manière opportuniste. En outre, les nœuds CR ne devraient pas perturber la qualité de réception des nœuds PR durant leur communication, et ce en limitant les interférences entre les deux [25].

Dans *les réseaux ad-hoc radio cognitif multi-hop sans infrastructure* , où il est difficile de réaliser une coordination entre les CRs et dans l'absence d'une entité centrale pour réglementer l'accès sur les fréquences , la fiabilité de diffusion des données est bien plus complexe. Dans cette perspective, l'étape importante en ayant la diffusion efficaces des données est de savoir *comment sélectionner les meilleures fréquences.* En fait, la sélection des fréquences joue un rôle essentiel dans la fiabilité de données disséminées. Si les nœuds CRs sélectionnent les fréquences de façon aléatoire, il y a très peu de chances que les récepteurs voisins choisissent également la même fréquence. Par conséquent, le choix aléatoire des fréquences dégrade sévèrement l'accessibilité aux données diffusées. En outre, quand les nœuds CRs choisissent aléatoirement les fréquences de transmission, il peut être possible qu'une transmission de PR soit sur la même fréquence, ce qui entraîne la génération d'interférences nuisibles aux nœuds PRs. Par conséquent, une nouvelle méthode de sélection de fréquences est requise afin de réduire le nombre d'interférences nuisibles aux nœuds PR, et maximiser les chances de délivrance des messages aux voisins récepteurs des nœuds CR, et augmenter ainsi la fiabilité des données disséminées.

Nous décrivons maintenant la contribution de cette thèse.

C.3 Contributions de la thèse

Dans la suite de ce paragraphe, nous décrivons d'abord nos contributions, puis nous décrirons la méthodologie adoptée dans cette thèse.

C.3.1 Solutions proposées

La première contribution de cette thèse est une stratégie de sélection de fréquences, nommée SURF, pour la diffusion de données dans les réseaux ad-hoc radio cognitifs multi-sauts .

Dans SURF, la classification des fréquences est réalisée sur la base d'inoccupation de la radio primaire et le nombre de voisins à radio cognitive utilisant ces fréquences. SURF prend des décisions efficaces et fiables de fréquences à la volée et recouvre les mauvais choix. Elle maintient les précédentes mauvaises predictions et adapte en conséquence les futures sélections de fréquence. Généralement, les stratégies de sélection de fréquence fournissent aux nœuds un moyen de sélection de fréquences de transmission. Par contre, SURF revêtit les nœuds CR à sélectionner les meilleures fréquences pour transmission et interceptions. Cela aidera à ajuster à la fois l'émetteur et le récepteur avec une forte probabilité sur la même fréquence. Par conséquent, SURF aura un nombre élevé de voisins sur la fréquence sélectionnée. De plus, SURF protège les nœuds PR en considérant l'inoccupation de PR dans la prise de décision, afin d'assurer une diffusion fiable et efficace des données.

La deuxième contribution de la thèse est le perfectionnement du simulateur de réseau NS-2 pour inclure le modèle d'activité de P.R. En fait, le simulateur de réseau NS-2 a été largement utilisé dans le domaine de recherche de réseaux sans fil. Nous avons également opté pour NS-2 dans notre étude basée simulation Néanmoins, étant donné que la recherche dans CRNs est très récente, un module complet et précis de simulation pour CRNs dans NS-2 n'était pas encore disponible. Afin de traiter un tel manque, nous avons modifié

NS-2 pour ajouter les fonctionnalités manquées de CRNs. Nous avons employé le patch de réseaux radios cognitifs (CRCN) de NS-2. Ce patch CRCN de NS-2 ne prend pas en charge l'activité des nœuds P.R. Ainsi, nous améliorons le patch CRCN de NS-2 afin d'inclure le modèle d'activité de PR. Par ailleurs, nous avons aussi modifié le protocole MAC afin d intégrer le modèle d'activité de PR. Plus de détails peuvent être trouvés dans le section 3.5 et l'appendix B.

Nous avons observé que les stratégies de sélection de fréquences sont fortement influencées par l'activité des nœuds à radio primaire. Nous étudierons l'impact de l'activité des nœuds à radio primaire sur quatre stratégies de sélection de fréquences. Cela constitue la troisième contribution de cette thèse.

La quatrième et la contribution finale de cette thèse est l'applicabilité de SURF. Dans cette perspective, nous proposons une architecture d'accès à internet basée sur la radio cognitive pour les réseaux endommagés. Nous discutons les détails architecturaux et le principe de fonctionnement de l'architecture proposée. Nous avons également passé en revue les enjeux et les défis de déploiement de cette nouvelle architecture. Enfin, nous discutons l'applicabilité de SURF dans le contexte de l'agrégation de fréquences et à cet égard, nous discutons une stratégie d'interférence basée sur l'agrégation de fréquences pour les réseaux radios cognitifs.

C.3.2 Méthodologie

Nous commençons notre analyse en examinant un modèle réaliste d'activité de P.R. Nous considérons le simulateur de réseau NS-2 pour effectuer les simulations et analyser SURF. Cependant, il n'y avait qu'un seul patch disponible qui supporte certaines fonctions partielles du réseau radio cognitif.

Ainsi, nous avons augmenté le simulateur de réseau NS-2 en incluant le modèle ON/OF d'activité de P.R. Nous avons également modifié le protocole MAC et mis en œuvre l'activité ON/OF. Nous avons alors effectué des simulations étendues dans des scénarios à un seul saut et multi-saut, afin d'analyser la performance de SURF, et l'a comparer à trois autres approches liées.

Les résultats de simulations ont révélé que la performance du réseau radio cognitif est fortement dépendante du modèle d'activité de nœuds PR. Par conséquent, nous élargissons notre but en étudiant et analysons l'activité des différents nœuds PR. Nous considérons quatre stratégies de sélection de fréquences et nous analysons la performance de ces stratégies par des simulations NS-2 dans différents modèles d'activité de nœuds PR. Par ailleurs, nous analysons comment ces stratégies répondent aux différentes activités de nœuds PR.

Dans cette thèse, nous avons également examiné les scénarios pratiques où SURF pourrait être mis en œuvre. Grâce à la simpliste nature du SURF, les situations post-catastrophe sont plus réalisable pour le déploiement de SURF. Ainsi, nous proposons une architecture d'accès à internet basée sur la radio cognitive pour le déploiement des réseaux en cas de catastrophes dans des environnements hostiles. En outre, nous discutons la faisabilité et l'applicabilité de SURF dans le cadre d'agrégation de fréquences. À cet égard, nous discutons stratégie d'interférence basée sur l'agrégation de fréquences, C-BOND.

C.4 Aperçu de la thèse

Ce document de thèse est structuré en six chapitres. Après ce chapitre, dans le chapitre 2, nous fournissons les défis de la diffusion des données et la classification des stratégies de sélection de fréquences dans les réseaux radios cognitifs. Dans le chapitre 3, nous discutons notre stratégie de sélection de fréquences SURF. En outre, nous abordons aussi les modifications de NS-2 dans le même chapitre. Nous discutons l'impact de l'activité des nœuds à radios primaires sur les stratégies de sélection de fréquences, tels que RD, HD, SB, et SURF, dans le chapitre 4. Nous discutons l'applicabilité et la faisabilité de SURF en chapitre 5. Nous concluons cette thèse en donnant des directions possibles pour la recherche future dans chapitre 6.

C.5 1ère Partie: SURF Méthode de sélection de fréquences

La stratégie de sélection de fréquence SURF est spécialement conçue pour les réseaux ad-hoc radios cognitifs. L'objectif général de SURF est d'augmenter la fiabilité des données diffusées dans les réseaux ad-hoc multi-sauts ; CRN. SURF est un système de paquets basé sur la sélections de fréquences de diffusion des données et non pas un algorithme de routage. Par conséquent, ni les tables de routage, ni les chemins de bout en bout sont maintenues par les nœuds CR. A chaque réception de paquet, les nœuds CRs choisissent la meilleure voie, et diffusent le paquet par la suite.

Avec SURF, chaque nœud CR classifie de façon autonome les fréquences disponibles sur la base d'inoccupation de PR sur ces fréquences. Cette classification est ensuite affinée en identifiant le nombre de CR sur chaque bande. La meilleure fréquence pour la transmission est celle qui a le plus grand taux d'inoccupation de PR et un plus grand nombre de voisins CR. En effet, le choix d'une fréquence ayant un petit nombre de CRs peut induire à un réseau déconnecté. Chaque CR après avoir classifier les fréquences disponibles, commute dynamiquement pour la meilleure et diffuse le message stocké. Par ailleurs, SURF essaye d'apprendre les précédentes mauvaises predictions de fréquences. Ce processus d'apprentissage permet une meilleure optimisation des futures predictions et aide les nœuds CR à recouvrir leurs mauvaises décisions de sélection de fréquences.

En outre, les CRs sans message à transmettre accomplissent la stratégie SURF afin d'accorder la *meilleure* fréquence pour la réception des données. En utilisant la même stratégie utilisée par l'émetteur au niveau du récepteur, on va permettre à des récepteurs dans des secteurs géographiques étroits de choisir avec une probabilité élevée les mêmes fréquences. Par conséquent, le nombre de voisins CRs sur la même fréquence sélectionnée va augmenter. Ceci est du au fait, qu'il est probable que les CRs dans le voisinage de l'émetteur aient le même taux d'inoccupation de PR, d'où les fréquences disponibles à l'émetteur CR sont également disponible à ses voisins avec une forte probabilité [63]. De ce fait, SURF augmente la probabilité de création d'une topologie connectée. Une fois qu'un paquet est reçu, chaque récepteur CR subit à nouveau la même procédure pour choisir la fréquence appropriée pour transmettre le message à son voisin.

La formule de calcul de poids de fréquences La stratégie SURF classifie les fréquences en assignant un poids $P_w^{(i)}$ pour chaque fréquence i Dans l'ensemble de fréquence C. Alors, chaque noeud à radio cognitive exécute SURF, et calcul localement le $P_w^{(i)}$ en utilisant la formule suivante:

$$\forall i \in C : P_w^{(i)} = PR_u^{(i)} \times CR_o^{(i)} \tag{C.1}$$

$P_w^{(i)}$ décrit le poids de la fréquence (i) qui est calculé en se basant sur l'inoccupation de PR (c-à-d. $PR_u^{(i)}$) et l'occupation CR $CR_o^{(i)}$) de la fréquence i (c.f. section 3.3 et section 3.4). Cependant, la fréquence est classée selon son poids et la meilleure fréquence (i.e., l'une qui offrent les plus élevés $P_w^{(i)}$) sera utilisée. Notons que lorsque la fréquence possède le meilleur poids mais au temps t elle est occupée, SURF réagit (i) en ne transmettant le paquet que sur la meilleure fréquence pondérée et (ii) en sélectionnant la prochaine meilleure fréquence pour la transmission de paquets pondérée. Notons également que lorsque toutes les fréquences sont occupés, aucun message n'est envoyé.

C.5.1 Comparaison de SURF

Dans cette section, nous évaluons la performance de SURF en le comparant avec trois approches liées i.e., Random (RD), Highest Degree (HD), and Selective Broadcasting (SB).

C.5.1.1 Protection de nœuds radio primaire

Dans cette section, nous caractérisons les interférences probables causés par des transmissions CR aux nœuds de PR pour SURF, RD, HD, et SB. Fig. C.2 compare le ratio d'interférences nuisibles pour la RD de quatre stratégies à savoir, HD, SB et du SURF, pour Ch = 5 et Ch = 10. Il peut être clairement vu dans la figure que SURF, comme attendu, provoque des interférences moins nocives pour les nœuds de PR, par rapport à la RD, HD, et SB. C'est principalement parce que, lorsque vous utilisez SURF, les nœuds CR sélectionnés sont ceux des chaînes qui ont une très forte probabilité d'être dans l'état OFF, réduisant ainsi les interférences PR. Notez que dans le SURF, si tous les canaux sont occupés, la transmission CR n'aura pas lieu. Ainsi, la valeur inférieure HIR pour le SURF sur la Fig. C.2 n'est représenté que dans le cas où tous les canaux sont occupés par les PR et une interférence probable serait causé si une transmission a eu lieu. En outre, lorsque le nombre de chaînes est faible, c'est à dire Ch = 5, la valeur des HIR est plus élevé que Ch = 10. Cela est dû au fait qu'un nombre aussi inférieur de canaux réduit les chances de trouver des nœuds CR PR-inoccupés pour leur transmission. En conséquence, SURF protège des nœuds de PR, en réduisant le nombre de collisions avec des radios primairs.

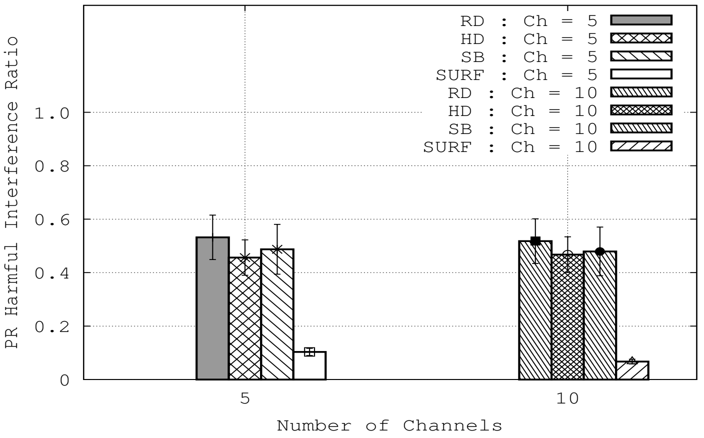


Figure C.2: PR harmful interference ratio pour RD, HD, SB and SURF, quand Ch=5 and Ch=10.

Table C.1: Average delivery ratio (dans %).

	PR=0		*PR ≠ 0 (cf. Table 3.1)*	
Strategy Name	**Ch=5**	**Ch=10**	**Ch=5**	**Ch=10**
RD	0.25	0.16	0	0
HD	0.18	0.18	0.02	0.02
SB	0.02	0.03	0	0
SURF	0.34	0.33	0.27	0.36

C.5.1.2 Diffusion Fiable des Données

Dans cette section, notre objectif est d'évaluer la fiabilité de la diffusion des données. Nous avons choisi deux paramètres pour évaluer la diffusion des données fiables: (1) ratio moyen de livraison, et (2) ratio de récepteurs cummulatifs.

Average Delivery Ratio: Afin de mieux observer l'impact sur le ratio de la livraison de telle voisinage dynamique, Fig. C.3 montre le ratio moyen de livraison par ID de nœud pour Ch = 5 et Ch = 10 lorsque l'activité PR égal à 0. De même, le tableau C.1 résume le rapport prestation globale moyenne de la Fig C.4 and Fig. C.3. Les résultats attestent que les faibles ratios obtenus de livraison sont principalement du à la création de topologies différentes

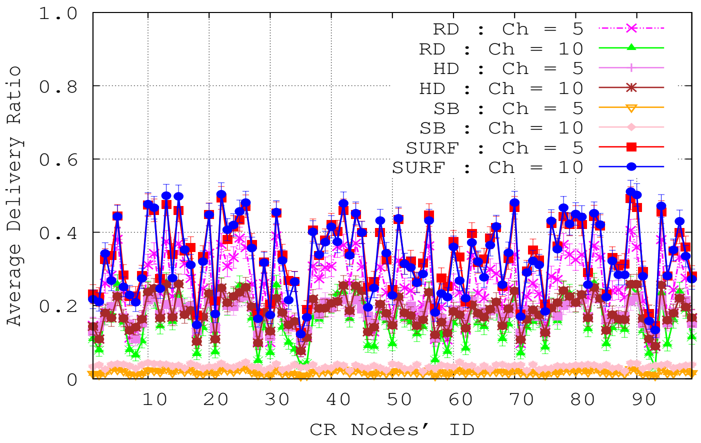


Figure C.3: CR Nodes' ID et average delivery ratio, quand PR activité egale à zero.

résultante de la disponibilité multi-canaux et la sélection de chaînes distribués par CR. Plus précisément, même si aucune concurrence existe PR, le ratio moyen de livraison maximal est inférieur à 35 %. Néanmoins, il est intéressant de noter que SURF est l'approche la moins touchée par les activités de RP: En prenant intelligemment profit des disponibilités des canaux, SURF est en mesure d'assurer un ratio de livraison stable, même lorsque la transmission CRS est en concurrence avec les PR.

Surtout, il est intéressant de noter que lors de l'augmentation du nombre de canaux, la performance SURF est également renforcée. Ce résultat est paradoxal puisque l'ajout de canaux rend la synchronisation entre l'émetteur et le récepteur (c'est à dire sélectionner le même canal) est plus difficile à réaliser. Cependant, en utilisant la métrique appropriée et surtout en employant la même stratégie à l'expéditeur et le destinataire, SURF réalise de meilleurs résultats lorsque plusieurs canaux sont disponibles.

Fig. C.4 compare le ratio moyen de livraison de RD, HD, SB et du SURF, pour Ch = 5 et CH = 10. SURF augmente considérablement le taux de livraison par rapport aux autres solutions. En particulier, pour Ch = 5, SURF garantit un ratio maximum de livraison d'environ 40 %, comparativement à près de 0% dans le cas de RD, HD, et SB. Et quand Ch = 10, SURF permet à certains nœuds d'atteindre un ratio maximal de livraison de 50 %, tandis que dans la RD, il est presque à 0% et 2 % en HD et SB.

En fait, RD, HD, et SB, ne garantissent pas que le canal sélectionné est inoccupé pour la transmission entraînant ainsi une diminution importante du ratio de livraison. Alors que

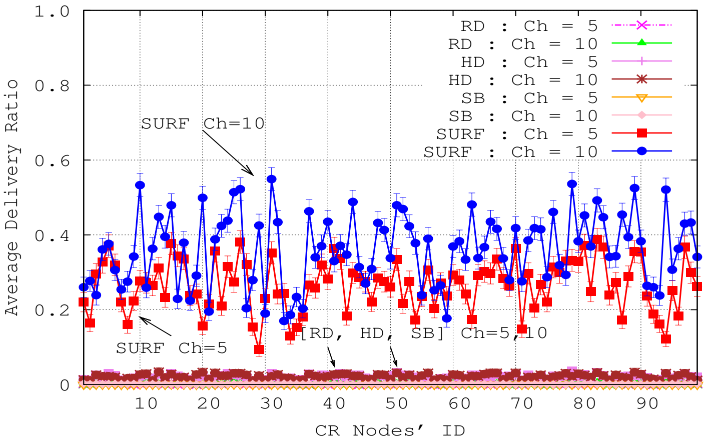


Figure C.4: CR Nodes' ID et average delivery ratio.

dans le SURF, le ratio moyen de livraison est plus élevé parce que les nœuds CR sélectionne le canal qui a $P^{*}_{OFF}(t)$ élevé et plus de voisins CR. Il est à noter que la diversité en termes de disponibilité des canaux et des activités de PR, et la faible densité conséquente du voisinage après le résulat de la sélection de CR canaux locaux dans la création de différentes topologies (par exemple, voisinage dynamique) à chaque transmission / entendant des nœuds CR. Ces problèmes rendent les choses difficiles à la réalisation d'un ratio de livraison plus élevé que SURF.

Ratio of Accumulative Receivers: Fig. C.5 compare le ratio de récepteurs cummulatif à chaque saut de communication (c'est à dire, jusqu'à ce que $itTTL = 0$) pour la RD, HD, SB, et le SURF. SURF surpasse les trois autres techniques dans tous les sauts. Au 1^{er}-Hop, en raison de la première transmission du message, aucune collision n'est présent. Dans ce cas, SURF fournit un ratio de 95% récepteurs pour le CH = 10 (80 % pour le CH = 5), contre 5 % pour la RD, 12% pour la HD, et 2 % pour SB. Avec la propagation du message et sa réplication naturelle dans le réseau, la probabilité de collisions augmente et, par conséquent, le ratio des récepteurs diminue à chaque nouveau saut, pour toutes les stratégies. Pourtant, SURF assure un meilleur taux de diffusion que d'autres stratégies. Ceci est obtenu grâce à la sélection du canal SURF, qui sélectionne les canaux offrant une forte probabilité pour la bonne livraison, ainsi que pour une bonne réception.

En résumé, les résultats dans la Fig. C.4 et Fig. C.5 confirment que SURF peut fournir de bonnes accessibilités du réseau, adapté à l'amélioration de la fiabilité de diffusion dans

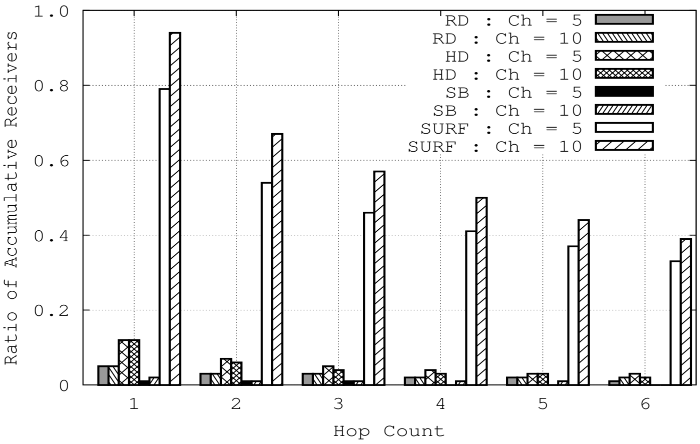


Figure C.5: Hop count et Ratio du accumulative receivers.

les réseaux ad-hoc multi-sauts radio cognitifs.

C.6 2eme Partie: Impact de l'activité des nœuds PR sur la stratégie de sélection de fréquences

La performance du réseau radio cognitif est fortement dépendante du modèle d'activité de nœuds à radio primaire. Dans cette thèse, nous étudions et analysons l'impact des différents modes d'activité de nœuds PRs sur les différentes stratégies de sélection de fréquences à savoir, la stratégie aléatoire (RD), la méthode de plus haut degré (HD), la diffusion sélective (SB) et y compris notre stratégie proposée pour la sélection des fréquences (SURF). Par ailleurs, nous avons aussi analysé l'adaptabilité de ces stratégies de sélection de fréquences aux différents modèles d'activités de nœuds PR. En particulier, en analysant notre stratégie de sélection de fréquences SURF [34] sous différents modèles d'activité PR (environnements sans fil), nous gagnons des idées qui nous aideront dans l'avenir pour mettre en place les différentes heuristiques de fréquences. Par les simulations NS-2, nous produisons différents modèlés d'activité PR et nous étudions à travers plusieurs paramètres de performance les réactions des approches.

Principales Conclusions. Les principales conclusions sont:

- Lorsque le système est libre (faible activité PR), chaque solution offre un gain acceptable. Parfois, une solution intelligente ne vaut pas la peine en raison de la complexité qu'elle introduit.

- Lorsque le système est proche de la capacité maximale (Haute activité de PR), toutes les solutions ont une mauvaise performance. Lorsque les fréquences sont entièrement occupées par PRs il n'y a pas de réelle opportunité pour la transmission, là aussi, le gain est très faible comparé à la complexité des solutions.
- Le cas intermittent est le cas où les solutions intelligentes doivent fonctionner. C'est là où SURF donne les meilleurs résultats et la région ciblée se sert des opportunités de communication.

C.7 3ème Partie: L'applicabilité de SURF

Dans la section précédente, nous avons discuté de l'impact d'activité de nœuds à radio primaire sur les stratégies de sélection de fréquence. Nous allons allé plus loin en envisageant deux scénarios d'application et discuter l'applicabilité et la faisabilité de SURF. À cet égard, nous présentons tout d'abord ci-après une architecture d'accès à internet basée sur la radio cognitive pour le déploiement des réseaux en cas de catastrophes dans des environnements hostiles. Deuxièmement, nous discutons d'une stratégie d'interférence basée sur l'agrégation de fréquences pour les réseaux radios cognitifs.

C.7.1 1ère Application: architecture d'accès à Internet

L'architecture d'accès à internet pour les réseaux radios cognitifs est une architecture à trois tiers adaptée à mettre en œuvre et déployer des applications réelles de réseaux radios cognitifs dans des environnements de communication contraignants. Un aperçu général de notre architecture est représenté dans la Fig. C.6. Les blocs constructifs de cette architecture sont: (1) dispositifs radio cognitifs (CR), (2) les routeurs mesh multi-radio cognitifs (CMR), et (3) le point d'accès a internet.

Dans cette architecture, nous considérons les réseaux partiellement endommagés comme étant des réseaux primaires et leurs nœuds comme des nœuds primaires. En effet, notre objectif est de détecter les communications courantes dans ces infrastructures partiellement endommagées afin de leur offrir une connectivité à d'autres parties de la même infrastructure, ou même à Internet.

Il est clair que l'interconnexion de différents réseaux en utilisant différentes technologies peut être très difficile, cependant, la souplesse de gestion du spectre et la dynamique offerte par le CRN peut aider à surmonter ces obstacles. Les dispositifs non-CR doivent communiquer avec les dispositifs CR afin de rétablir leur connectivité à d'autres parties du réseau et à Internet.

Pratiquement, lorsque les dispositifs non-CR, ont besoin de communiquer avec les dispositifs CR, ils ont d'abord besoin de les détecter. Pour atteindre cet objectif, les dispositifs CR peuvent annoncer leur présence aux autres dispositifs non-CR. Par ailleurs, les dispositifs CR devront écouter les canaux afin de savoir si les données transmises par un dispositif non-CR sont pour un dispositif non-CR ou bien pour un dispositif CR, afin de pouvoir accéder à l'Internet.

Cette architecture peut être exploitée dans deux scénarios : avec un seul saut et multi-sauts. Les dispositifs CR communiquent directement avec les routeurs mesh multi-radio cognitifs dans le scénario d'un seul saut, tandis que dans un scénario multi-sauts, les dispositifs CR créent des chemins multi-sauts pour atteindre le plus proche routeur mesh multi-radio cognitifs.

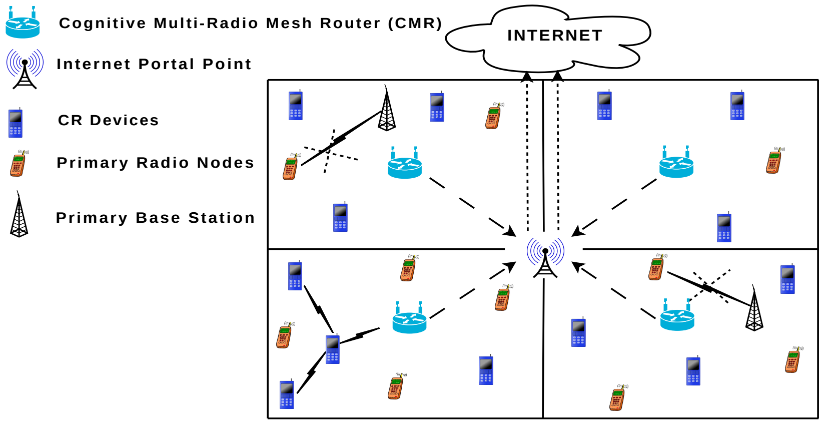


Figure C.6: Architecture d'accès à Internet

Utilisation de SURF dans les dispositifs CR et CMRs Lorsque les dispositifs CR veulent charger leurs données à l'Internet, ils sont exigés de communiquer avec le routeur mesh multi-radio cognitif sur une fréquence particulière. Sans aucune stratégie intelligente de sélection de fréquences, la concentration de tous les dispositifs de radio cognitive sur une fréquence particulière pourrait conduire à des problèmes de contention et de collision, ce qui réduit encore la connectivité à Internet. Ainsi, la sélection de fréquence joue un rôle essentiel pour relayer les données d'une manière efficace et fiable. Ce relais de données peut être effectué entre les dispositifs à radio cognitive et les routeurs mesh multi-radio cognitif, ou parmi les dispositifs à radio cognitive, qui opère dans le mode multi-sauts pour atteindre le routeur mesh multi-radio cognitif.

Dans les scénarios où les routeurs mesh multi-radio cognitifs sont responsables de l'affectation de fréquences aux dispositifs CR, SURF pourrait être exécutée par ces routeurs. Le mode de communication entre les dispositifs à radio cognitive et les routeurs mesh multi-radio cognitifs est via un seul saut. Il pourrait y avoir certains scénarios où les dispositifs CR ne peuvent pas atteindre directement les routeurs mesh multi-radio cognitifs pour relayer les données vers l'Internet. Ainsi, les dispositifs CR ont besoin de créer un réseau multi-sauts. Dans un scénario de réseau multi-sauts, la tâche de relayer les données aux routeurs mesh multi-radio cognitifs sera beaucoup plus difficile. Afin d'atteindre les routeurs mesh multi-radio cognitifs, les dispositifs à radio cognitive doivent communiquer avec d'autres dispositifs à radio cognitive et créent ainsi un réseau multi-sauts.

Cependant, le principal défi est de savoir comment sélectionner une fréquence fiable pour les dispositifs CR. La sélection d'une fréquence fiable est très difficile en raison de la diversité dans le nombre de fréquences disponibles et l'absence d'une autorité centralisée. Ainsi, SURF pourrait être implémenté par des dispositifs CR dans des scénario multi-sauts, étant donné que la sélection de fréquence est effectuée d'une manière distribuée et en se basant uniquement sur les informations déduites localement par les dispositifs CR. Par ailleurs, dans les situations post-catastrophe, SURF peut encore être améliorée en intégrant les priorités aux messages urgents pour aider les victimes de ces catastrophes.

C.7.2 2ème Application: Agrégation de fréquences

Avec les progrès de la technologie et la disponibilité d'appareils moins chers, les dispositifs sans fil à bande passante très gourmand peuvent être vus autour de nous. Ces dispositifs nécessitent une large bande passante due à des applications de nouvelles générations telles que la VoIP, la vidéo et le streaming direct. Comme Shanon à prouvé théoriquement que le taux de temps augmente linéairement avec la bande passante, mais seulement logarithmiquement avec la puissance du signal ou SNR. Ainsi, l'approche pour faire face au problème de consommation de la bande passante consiste à adapter la largeur de la fréquence [137] en combinant deux ou plusieurs voies, c'est à dire *agrégér les fréquences* [138]. Dans *l'agrégation de fréquences*, un ensemble de fréquences contiguës non chevauchées sont liées ensemble afin de créer une seule fréquence à large bande. Il en résulte une très grande bande passante agrégée et une augmentation du taux de transmission de paquets, ainsi qu'une meilleure satisfaction des besoins de nœuds en terme de bande passante.

Dans les réseaux sans fil traditionnels, l'agrégation de fréquence a été employée pour l'équilibrage de charge [137], le provisionnement de QoS [139] etc. La version provisoire courante d'IEEE 802.11n discute également de l'agrégation de fréquences dans le spectre 2.4GHz et 5GHz, où deux fréquences 20MHz sont agrégées dans une seule fréquence 40MHz pour améliorer le taux de transmission [140]. Cependant, des techniques mentionnées ci-dessus ne peuvent pas être directement appliquées aux réseaux radio cognitifs (CRNs) dus aux contraintes imposées par les nœuds à radio primaire (PR), tels que l'inoccupation variable dans le temps par les PR. Par ailleurs, pour la réception des paquets de données, le nœud émetteur à radio cognitives et (CR) et le nœud récepteur devraient agrégés les mêmes canaux de fréquence. Ainsi, des techniques intelligentes d'agrégation de canaux de fréquences sont exigées dans CRNs qui garde en considération l'occupation de PR, et leur cause moins d'interférence et ainsi accorde aux nœuds émetteur-récepteur CR les mêmes canaux de fréquences agrégés. Il est à noter que dans le cadre des réseaux radios cognitifs (norme d'IEEE 802.22), l'agrégation de fréquences est maintenant praticable [141].

Dans les réseaux radios cognitifs, lorsque les nœuds CR transmettent sur les fréquences qui sont adjacentes aux bandes de radio primaire, cause des interférences nuisibles aux nœuds PR [112]. Pour cette raison, lors de l'agrégation de canaux de fréquences, les informations concernant l'occupation des fréquences adjacentes est crucial dans l'atténuation des interférences à ces nœuds à radio primaire [142]. Ce problème est mentionné en tant que problème d'interférence de la fréquence adjacent (ACI) [143], [91] dans les réseaux sans fil traditionnels. Maintenir ceci dans l'esprit, la commission fédérale de communication (FCC) dans la norme IEEE 802.22 a restreint les dispositifs fixes d'émettre sur les fréquences adjacents de i^{th} fréquence active. En outre, dans CRN, la première priorité est de protéger les nœuds PR, par conséquent, les fréquences non-recouvertes seront pas utilisées pour la communication. En résumé, il est essentiel, mais extrêmement difficile de considérer l'interférence de fréquence adjacente lors d'agrégation de fréquences à cause de temps variant d'occupation de PR.

Contrairement aux approches précédentes [65], [117], [144], qui ne considèrent pas le problème d'interférence des canaux de fréquences adjacents, nous examinons attentivement le problème d'interférence dans le canal de fréquence adjacent, tout en effectuant une agrégation de fréquences. En outre, nous proposons que l'affectation de fréquence doive être réalisée d'une manière à envisager l'occupation de canaux de fréquences adjacents par les PRs. Plus précisément, le problème principal que nous abordons dans ce contexte est it comment effectuer l'agrégation de canaux de fréquences dynamiquement pour répondre aux exigences de bande passante des nœuds CRs, tout en considérant l'occupation des fréquences par les PRs et les interférences dans les fréquences adjacents . à cet égard, nous proposons C-Bond, une méthode dynamique d'agrégation de fréquences adjacentes pour les réseaux radios cognitifs a un seul saut.

Dans C-BOND, d'abord les fréquences inoccupées sont caractérisées en différents types en se basant sur des canaux de fréquences adjacents libres. Cette caractérisation est réalisée sur l'analyse de [142], dans lequel les auteurs classent les canaux de fréquences disponibles en occupation PR de leur canaux adjacents. Dans la deuxième étape, en se basant sur notre mécanisme proposée, les canaux sont agrégés pour créer une bande passante plus large en fonction de ces différents types. Dans la dernière étape, les fréquences agrégées sont affectées à des nœuds CR pour la communication. La stratégie de distribution proposée pour la sélection est de nature adaptative et bien adaptée pour les réseaux radios cognitifs.

L'utilisation de SURF dans la sélection stable et gratuites lors de l'agrégation de fréquences: Cela signifie, que les nœuds PR peuvent réapparaître sur la fréquence agrégée. Par conséquent, la fréquence agrégée est découpée et rendue aux nœuds PR pour la transmission. La question est, comment la transmission doit être remise en toute transparence à une autre fréquence agrégée avec la même taille de la bande passante. Une approche pour traiter ce problème est de maintenir un ensemble de fréquences agrégées au niveau de l'AP. Cet ensemble contient la liste des fréquences les plus probables pour l'agrégation à l'égard de leurs tailles. Par exemple, quand une fréquence agrégée avec deux sous-fréquences est découpée, par la suite l'AP choisit et assigne la fréquence agrégée suivante qui a la même taille au nœud CR.

Il est à noter que, si l'ensemble de fréquences agrégées est déjà utilisé par les nœuds voisins CR et aucune fréquences agrégée gratuite n'est disponible, alors le nœud CR peut utiliser la fréquence non-agrégé disponible pour la communication. Cependant, cela réduira le débit de données du nœud CR.

Nous discutons maintenant comment SURF pourrait être utilisée en conjonction avec le C-BOND. En fait, la fréquence agrégée stable et gratuite ne peut être sélectionnée si l'activité de PR est considérée lors de la sélection de la fréquence. Comme nous l'avons déjà mentionné SURF considère spécialement l'activité PR pendant la sélection de la fréquence et provoque moins d'interférences nuisibles aux nœuds à radio primaire (cf. section 3.7.1). Ainsi, SURF peut être utilisée pour sélectionner les canaux de fréquences stables.

C.8 Conclusion

Dans cette thèse, nous proposons SURF, une nouvelle méthode distribuée de sélection de fréquences pour la dissémination fiable de données dans un réseau radio cognitif multi-sauts. SURF classifie les fréquences radio disponibles en fonction de l'occupation des fréquences des nœuds à radio primaire et le nombre de noeuds à radio cognitive utilisant ces fréquences.

Les résultats de simulation obtenus par NS-2 confirment que SURF, comparée aux autres approches liées, est une stratégie efficace dans la sélection des meilleures fréquences de diffusion de données. Nous avons aussi constaté que les stratégies de sélection de fréquences sont considérablement influencées par l'activité des nœuds à radio primaire. Dans la suite ce cette thèse, nous étudierons et analyserons l'impact des modèles d'activités des nœuds PR sur les différentes stratégies de sélection de fréquences. Les résultats de simulations obtenus par NS-2 confirment que SURF superforme les autres stratégies de sélection de fréquences en termes de taux de délivrance et causes d'interférences avec les nœuds PR, dans tous les modèles d'activités de nœuds primaires. Enfin, dans cette thèse, nous allons encore plus loin en vérifiant l'applicabilité et la faisabilité de SURF. Dans cette perspective, d'abord, nous proposons une architecture d'accès à internet basée sur la radio cognitive pour les réseaux partiellement endommagés. Nous discutons des détails architecturaux et le principe de fonctionnement de l'architecture proposée. Nous avons également passé en revue les enjeux et les défis de déploiement de cette nouvelle architecture. Deuxièmement, nous discutons de l'applicabilité de SURF dans le contexte de l'agrégation de fréquences et à cet égard, nous discutons d'une stratégie d'interférence basée sur l'agrégation de fréquences pour les réseaux radios cognitifs.

References

[1] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: a survey,” *Computer Networks: The International Journal of Computer and Telecommunications Networking*, vol. 50 , Issue 13, pp. 2127 – 2159, 2006.

[2] “The xg vision, version 2,” 2004. [Online]. Available: http://www.ir.bbn.com/~ramanath/pdf/rfc_vision.pdf

[3] R. Leschhorn and B. Buchin, “Military software defined radios- rohde and schwarz status and perspective,” in *Proceedings of the SDR 04 Technical Conference and Product Exposition*, 2004.

[4] O. Younis, L. Kant, K. Chang, and K. Young, “Cognitive manet design for mission-critical networks,” *IEEE Communications Magazine*, pp. 64–71, October 2009.

[5] S. Ball, A. Ferguson, and T. W. Rondeau, “Consumer applications of cognitive radio defined networks,” in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN’ 05)*, 8-11 Nov 2005, pp. 518–525.

[6] M. M. Buddhikot, “Understanding dynamic spectrum access: Models, taxonomy, and challenges,” in *DySPAN*, April 2007, pp. 649–663.

[7] J. M. Chapin and W. H. Lehr, “The path to market success for dynamic spectrum access technology,” *IEEE Communications Magazine*, vol. 45(5), pp. 96–103, 2007.

[8] A. Gorcin and H. Arslan, “Public safety and emergency case communications: Opportunities from the aspect of cognitive radio,” in *IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySpan)*, Chicago, IL, 2008.

[9] S. Majid and K. Ahmed, “Post-disaster communications: A cognitive agent approach,” in *Seventh International Conference on Networking*, 2008.

[10] J. Wang, M. Ghosh, and K. Challapali, “Emerging cognitive radio applications: A survey,” *Communications Magazine, IEEE*, vol. 49, no. 3, pp. 74 –81, march 2011.

[11] P. Phunchongharn, E. Hosssain, D. Niyato, and S. Camorlinga, “A cognitive radio system for e-health applications in a hospital environment,” *IEEE Wireless Communications Magazine*, pp. 20–28, Feburary 2010.

[12] S. Feng, Z. Liang, and D. Zhao, “Providing telemedicine services in an infrastructure-based cognitive radio network,” *IEEE Wireless Communications Magazine*, pp. 96–103, Feburary 2010.

[13] M. Buddhikot, P. Kolodzy, S. Miller, K. Ryan, and J. Evans, "Dimsumnet: New directions in wireless networking using coordinated dynamic spectrum access," in *Sixth IEEE International Symposium on World of Wireless Mobile and Multimedia Network (WoWMoM)*, 2005, pp. 78 – 85.

[14] M. V. D. Schaar and F. Fu, "Spectrum access games and strategic learning in cognitive radio networks for delay-critical applications," *Proceedings of the IEEE*, vol. 97, No. 4, pp. 720–740, 2009.

[15] A. K. M. Azad and J. Kamruzzaman, "A framework for collaborative multi class heterogeneous wireless sensor networks," in *IEEE ICC*, May 2008, pp. 4396–4401.

[16] S.-S. Byun, I. Balasingham, and X. Liang, "Dynamic spectrum allocation in wireless cognitive sensor networks: Improving fairness and energy efficiency," in *IEEE VTC*, Sep. 2008, pp. 1–5.

[17] S. Gao, L. Qian, D. R. Vaman, and Q. Qu, "Energy efficient adaptive modulation in wireless cognitive radio sensor networks," in *IEEE ICC*, June 2007, pp. 3980–3986.

[18] S. Gao, L. Qian, and D. R. Vaman, "Distributed energy efficient spectrum access in wireless cognitive radio sensor networks," in *Proc. IEEE WCNC*, April 2008, pp. 1442–1447.

[19] O. B. Akan, O. B. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Network*, vol. 23, issue 4, pp. 34–40, 2009.

[20] V.Fodor, R.Thobaben, and B. et al., "Sensor networks for cognitive radio: Theory and system design," in *ICT Mobile Summit*, June 2008.

[21] "Sendora project." [Online]. Available: http://www.sendora.eu/

[22] H. H. Pham, Y. Zhang, P. E. Engelstad, T. Skeie, and F. Eliassen, "Optimal cooperative spectrum sensign in cogntive sensor networks," in *IWCMC*, Leipzig, Germany, June 2009, pp. 1073–1079.

[23] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, 1999.

[24] FCC, "Spectrum policy task force (sptf), report of the spectrum efficiency wg," Nov. 2002.

[25] H. Khalife, S. Ahuja, N. Malouch, and M. Krunz, "Probabilistic path selection in opportunistic cognitive radio networks," in *proceedings of the IEEE globecom conference*, 30 Nov - 4 Dec 2008, pp. 1–5.

[26] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, "Crahns: Cognitive radio ad hoc networks," *Ad Hoc Networks*, vol. 7, issue 5, pp. 810–836, July 2009.

[27] H. B. Salameh and M. Krunz, "Channel access protocols for multihop opportunistic networks: challenges and recent developments," *IEEE Network*, vol. 23, no. 4, pp. 14 –19, july-august 2009.

[28] M. Sherman, A. N. Mody, R. Martinez, C. Rodriguez, and R. Reddy, "Ieee standards supporting cognitive radio and networks, dynamic spectrum access, and coexistence," *IEEE Communications Magazine*, vol. 46, issue 7, pp. 72–79, 2008.

[29] [Online]. Available: http://www.mangocomm.com/

[30] [Online]. Available: http://gnuradio.org/redmine/projects/gnuradio/wiki

[31] Z. Miljanic, I. Seskar, K. Le, and D. Raychaudhuri, "The winlab network centric cognitive radio platform - winc2r," in *CrownComm*, 2007.

[32] [Online]. Available: http://www.flex-radio.com/

[33] [Online]. Available: http://www.orbit-lab.org/

[34] M. H. Rehmani, A. C. Viana, H. Khalife, and S. Fdida, “Improving data dissemination in multi-hop cognitive radio ad-hoc networks,” in *3rd International ICST Conference on Ad Hoc Networks (ADHOCNETS 2011), Paris, France*, 21-23 Sep 2011.

[35] ——, “Surf: A distributed channel selection strategy for data dissemination in multihop cognitive radio networks,” *Submitted to: Computer Communications Elsevier Journal*, May 2011.

[36] M. H. Rehmani, “Channel assortment strategy for reliable communication in multi-hop cognitive radio networks,” in *Proceedings of the 11th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM 2010), Extended Abstract*, Montreal, QC, Canada, 14- 17 June 2010.

[37] M. H. Rehmani, A. C. Viana, H. Khalife, and S. Fdida, “Activity pattern impact of primary radio nodes on channel selection strategies,” in *Proceedings of the 4th International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART’11), in conjunction with ISABEL 2011, Barcelona, Catalonia, Spain,*, 26-29 Oct 2011.

[38] ——, “A cognitive radio based internet access framework for disaster response network deployment,” in *In Proceedings of the 3rd International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART’10), in conjunction with ISABEL 2010, Rome, Italy*, 08-10 Nov 2010.

[39] S.-Y. Ni, Y.-C. Tseng, Y.-S. Chen, and J.-P. Sheu, “The broadcast storm problem in a mobile ad hoc network,” in *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM ’99)*, 1999.

[40] K. Rostamzadeh and S. Gopalakrishnan, “Analysis of emergency message dissemination in vehicular networks,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, march 2011, pp. 575 –580.

[41] J.-F. Lee, C.-S. Wang, and M.-C. Chuang, “Fast and reliable emergency message dissemination mechanism in vehicular ad hoc networks,” in *IEEE Wireless Communications and Networking Conference (WCNC)*, april 2010, pp. 1 –6.

[42] A. T. Erman and P. Havinga, “Data dissemination of emergency messages in mobile multi-sink wireless sensor networks,” in *The 9th IFIP Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, june 2010, pp. 1 –8.

[43] M. Vecchio, A. C. Viana, A. Ziviani, and R. Friedman, “Deep: Density-based proactive data dissemination protocol for wireless sensor networks with uncontrolled sink mobility,” *Computer Communications*, vol. 33, no. 8, pp. 929 – 939, 2010, ¡ce:title¿Special Section on Hot Topics in Mesh Networking¡/ce:title¿. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0140366410000125

[44] A. C. Viana, T. Herault, T. Largillier, S. Peyronnet, and F. Zaïdi, “Supple: a flexible probabilistic data dissemination protocol for wireless sensor networks,” in *Proceedings of the 13th ACM international conference on Modeling, analysis, and simulation of wireless and mobile systems*, ser. MSWIM ’10. New York, NY, USA: ACM, 2010, pp. 385–392. [Online]. Available: http://doi.acm.org/10.1145/1868521.1868586

[45] G. Zyba, G. Voelker, S. Ioannidis, and C. Diot, “Dissemination in opportunistic mobile ad-hoc networks: The power of the crowd,” in *Proceedings IEEE INFOCOM*, april 2011, pp. 1179 –1187.

[46] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, and F. Silva, "Directed diffusion for wireless sensor networking," *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 2 – 16, feb 2003.

[47] M. Heissenbuttel, T. Braun, M. Walchli, and T. Bernoulli, "Optimized stateless broadcasting in wireless multi-hop networks," in *25th IEEE International Conference on Computer Communications INFOCOM*, april 2006, pp. 1 –12.

[48] O. Liang, Y. A. Sekercioglu, and N. Mani, "A survey of multipoint relay based broadcast schemes in wireless ad hoc networks," *Communications Surveys Tutorials, IEEE*, vol. 8, no. 4, pp. 30 –46, quarter 2006.

[49] W. Ya-feng, X. Yin-long, C. Guo-liang, and W. Kun, "On the construction of virtual multicast backbone for wireless ad hoc networks," in *IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, oct. 2004, pp. 294 – 303.

[50] J. Wieselthier, G. Nguyen, and A. Ephremides, "On the construction of energy-efficient broadcast and multicast trees in wireless networks," in *Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM*, vol. 2, 2000, pp. 585 –594 vol.2.

[51] Y.-C. Tseng, S.-Y. Ni, and E.-Y. Shih, "Adaptive approaches to relieving broadcast storms in a wireless multihop mobile ad hoc network," in *21st International Conference on Distributed Computing Systems*, apr 2001, pp. 481 –488.

[52] Z. Haas, J. Halpern, and L. Li, "Gossip-based ad hoc routing," in *Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM*, vol. 3, 2002, pp. 1707 – 1716 vol.3.

[53] R. Simon, L. Huang, E. Farrugia, and S. Setia, "Using multiple communication channels for efficient data dissemination in wireless sensor networks," in *IEEE International Conference on Mobile Adhoc and Sensor Systems Conference.*, nov. 2005, pp. 10 pp. –439.

[54] D. Starobinski and W. Xiao, "Asymptotically optimal data dissemination in multichannel wireless sensor networks: Single radios suffice," *Networking, IEEE/ACM Transactions on*, vol. 18, no. 3, pp. 695 –707, june 2010.

[55] L. Anantharamu, B. Chlebus, D. Kowalski, and M. Rokicki, "Deterministic broadcast on multiple access channels," in *Proceedings IEEE INFOCOM, 2010*, march 2010, pp. 1 –5.

[56] A. Asterjadhi, R. Kumar, T. La Porta, and M. Zorzi, "Broadcasting in multi channel wireless networks in the presence of adversaries," in *8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, june 2011, pp. 377 –385.

[57] A. Al-Mogren, "Energy adaptive approach in a multi-channel dissemination-based network," in *New Technologies, Mobility and Security, NTMS '08.*, nov. 2008, pp. 1 –6.

[58] W. feng Lv, F. liang Wang, and T. yu Zhu, "A greedy strategy of data dissemination over multi-channel in mobile computing environments," in *3rd International Conference on Advanced Computer Theory and Engineering (ICACTE)*, vol. 5, aug. 2010, pp. V5–322 –V5–326.

[59] L. Sun and W. Wang, "On distribution and limits of information dissemination latency and speed in mobile cognitive radio networks," in *Proceedings IEEE INFOCOM*, april 2011, pp. 246 –250.

[60] L. Yang, L. Cao, H. Zheng, and E. Belding, "Traffic-aware dynamic spectrum access," in *Proceedings of The Fourth International Wireless Internet Conference (WICON 2008)*, Hawaii, USA, 17-19, November 2008.

[61] C. Cordeiro, K. Challapali, D. Birru, and S. N. Shanka, “Ieee 802.22: An introduction to the first wireless standard based on cognitive radios,” *Journal of Communications*, vol. 1 (1), pp. 38–47, 2006.

[62] M. Hoyhtya, S. Pollin, and A. Mammela, “Classification-based predictive channel selection for cognitive radios,” in *IEEE ICC*, May 2010.

[63] Q. Zhao, L. Tong, A. Swami, and Y. Chen, “Decentralized cognitive mac for opportunistic spectrum access in ad hoc networks: A pomdp framewrok,” *IEEE Journal on Selected Areas in Communications*, vol. 25, No. 3, pp. 589–600, 2007.

[64] D. Niyato and E. Hossain, “Competitive spectrum sharing in cognitive radio networks: A dynamic game approach,” *IEEE Transactions on wireless communications*, vol. 7 (7), pp. 2651–2660, July 2008.

[65] H. Rahul, N. Kushman, D. Katabi, C. Sodini, and F. Edalat, “Learning to share: Narrowband-friendly wideband wireless networks,” in *ACM SIGCOMM*, vol. 38 , Issue 4, SEATTLE, WA, USA, 17-22 AUGUST 2008, pp. 147–158.

[66] F. Hou and J. Huang, “Dynamic channel selection in cognitive radio network with channel heterogeneity,” in *IEEE Globecom*, 2010.

[67] V. S. Rao, R. V. Prasad, C. Yadati, and I. Niemegeers, “Distributed heuristics for allocating spectrum in cr ad hoc networks,” in *IEEE Globecom*, 2010.

[68] G. D. Nguyen and S. Kompella, “Channel sharing in cognitive radio networks,” in *MILCOM*, 2010.

[69] P. Anggraeni, N. Mahmood, J. Berthod, N. Chaussonniere, L. My, and H. Yomo, “Dynamic channel selection for cognitive radios with heterogenous primary bands,” *Wireless Personal Communications*, vol. 45, pp. 369–384, 2008, 10.1007/s11277-008-9464-7. [Online]. Available: http://dx.doi.org/10.1007/s11277-008-9464-7

[70] P. A. K. Acharya, S. Singh, and H. Zheng, “Reliable open spectrum communications through proactive spectrum access,” in *TAPAS*, 2006.

[71] S.-U. Yoon and E. Ekici, “Voluntary spectrum handoff: A novel approach to spectrum management in crns,” in *ICC*, 2010.

[72] Q. Xiao, Y. Li, M. Zhao, S. Zhou, and J. Wang, “Opportunistic channel selection approach under collision probability constraint in cognitive radio systems,” *Computer Communications*, vol. 32 (18), pp. 1914–1922, 2009.

[73] Q. Zhao, S. Geirhofer, L. Tong, and B. M. Sadler, “Opportunistic spectrum access via periodic channel sensing,” *IEEE Transactions on Signal Processing*, vol. 56 (2), pp. 785–796, 2008.

[74] H. Wang, J. Ren, and T. Li, “Resource allocation with load balancing for cogntive radio networks,” in *IEEE GlobeCom*, 2010.

[75] L.-C. Wang, C.-W. Wang, and F. Adachi, “Load-balancing spectrum decision for cognitive radio networks,” *IEEE Journal on Selected Areas in Communications*, vol. 29 (4), pp. 757–769, April 2011.

[76] Q. D. Xue Feng, S. Guangxi, and L. Yanchun, “Smart channel swiching in cognitive radio networks,” in *CISP*, 2009.

[77] A. C.-C. Hsu, D. S.-L. Wei, and C.-C. J. Kua, “A cognitive mac protocol using statistical channel allocation for wireless ad-hoc networks,” in *WCNC*, 2007.

[78] R.-T. Ma, Y.-P. Hsu, and K.-T. Feng, “A pomdp-based spectrum handoff protocol for partially observable cognitive radio networks,” in *WCNC*, 2009.

[79] Y. Song and J. Xie, “Common hopping based proactive spectrum handoff in cogntive radio ad hoc networks,” in *GlobeCom*, 2010.

[80] P. Zhu, J. Li, and X. Wang, “A new channel parameter for cognitive radio,” in *CrownCom*, 2007.

[81] H. P. Shiang and M. V. D. Schaar, “Delay-sensitive resource management in multi-hop cognitive radio networks,” in *IEEE DySpan*, 2008.

[82] J. Zhao, H. Zheng, and G. H. Yang, “Distributed coordination in dynamic spectrum allocation networks,” in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Baltimore, Maryland, USA, 8-11 November 2005, pp. 259–268.

[83] J. Vartiainen, M. Hoyhtya, J. Lehtomaki, and T. Braysy, “Priority channel selection based on detection history database,” in *CROWNCOM*, 2010.

[84] L. Yang, L. Cao, and H. Zheng, “Proactive channel access in dynamic spectrum networks,” *Elsevier Physical Communications Journal*, vol. vol (1), pp. 103–111, 2008.

[85] M. Hoyhtya, S. Pollin, and A. Mammela, “Performance improvement with predictive channel selection for cognitive radios,” in *First International Workshop on Cognitive Radio and Advanced Spectrum Management,CogART 2008.*, Denmark, Feburary 2008, pp. 1–5.

[86] T. C. Clancy and B. D. Walker, “Predictive dynamic spectrum access,” in *Proc. SDR Forum Technical Conference*, Orlando, Florida, USA, Nov 2006.

[87] X. Liu and S. N., “Sensing-based opportunistic channel access,” *Mobile Networks and Applications*, vol. 11, pp. 577–591, 2006, 10.1007/s11036-006-7323-x. [Online]. Available: http://dx.doi.org/10.1007/s11036-006-7323-x

[88] S. Fourati, S. Hamouda, and S. Tabbane, “Rmc-mac: A reactive multi-channel mac protocol for opportunistic spectrum access,” in *4th IFIP International Conference on New Technologies, Mobility and Security (NTMS)*, feb. 2011, pp. 1 –5.

[89] W. Hu, D. Willkomm, M. Abusubaih, J. Gross, G. Vlantis, M. Gerla, and A. Wolisz, “Cognitive radios for dynamic spectrum access - dynamic frequency hopping communities for efficient ieee 802.22 operation,” *IEEE Communications Magazine*, vol. 45, no. 5, pp. 80 –87, may 2007.

[90] Y. R. Kondareddy and P. Agrawal, “Selective broadcasting in multi-hop cognitive radio networks,” in *IEEE Sarnoff Symposium*, Princeton, New Jersy, 28-30 April 2008, pp. 1–5.

[91] A. S. S. Mishra and R. Brodersen, “Cooperative sensing among cognitive radios,” in *IEEE ICC*, 2006.

[92] N. H. A. Sahai and R. Tandra, “Some fundamental limits on cognitive radios,” in *42 Allerton conference on Communication, Control and Computing*, 2004.

[93] R. T. A. Sahai and N. Hoven, “Opportunistic spectrum use for sensor networks: the need for local cooperation,” in *IPSN*, 2006.

[94] G. Ganesan and Y. G. Li, “Cooperative spectrum sensing in cognitive radio networks,” in *IEEE DySPAN*, November 2005.

[95] A. Ghasemi and E. S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *IEEE DySPAN*, November 2005.

[96] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Proceedings of Asilomar conference on signals, systems and computers*, 2004.

[97] C.-W. Wang, L.-C. Wang, and F. Adachi, "Modeling and analysis for reactive-decision spectrum handoff in cognitive radio networks," in *IEEE Global Telecommunications Conference (GLOBECOM 2010)*, dec. 2010, pp. 1 –6.

[98] L.-C. Wang and C.-W. Wang, "Spectrum handoff for cognitive radio networks: Reactive-sensing or proactive-sensins?" in *IEEE International Performance, Computing and Communications Conference (IPCCC 2008)*, 2008.

[99] G. Salami, A. Attar, a. R. T. Oliver Holland, and H. Aghvami, "A comparison between the centralized and distributed approaches for spectrum management," *IEEE Communications Surveys and Tutorials*, vol. 13, No. 2, pp. 274–290, 2011.

[100] M. Pereirasamy, J. Luo, M. Dillinger, and C. Hartmann, "Dynamic inter-operator spectrum sharing for umts fdd with displaced cellular networks," in *IEEE Wireless Communications and Networking Conference*, vol. 3, march 2005, pp. 1720 – 1725 Vol. 3.

[101] M. Buddhikot and K. Ryan, "Spectrum management in coordinated dynamic spectrum access based cellular networks," in *First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN'05*, nov. 2005, pp. 299 –307.

[102] R. Kulkarni and S. A. Zekavat, "Traffic-aware inter-vendor dynamic spectrum allocation: performance in multi-vendor environments," in *Proceedings of the 2006 international conference on Wireless communications and mobile computing*, ser. IWCMC '06. New York, NY, USA: ACM, 2006, pp. 85–90. [Online]. Available: http://doi.acm.org/10.1145/1143549.1143569

[103] P. Leaves, K. Moessner, R. Tafazolli, D. Grandblaise, D. Bourse, R. Tonjes, and M. Breveglieri, "Dynamic spectrum allocation in composite reconfigurable wireless networks," *IEEE Communications Magazine*, vol. 42, no. 5, pp. 72 – 81, may 2004.

[104] J. Zhu and S. Li, "Channel allocation mechanisms for cognitive radio networks via repeated multi-bid auction," in *ICWMMN 2006*, 2006.

[105] D. Niyato and E. Hossain, "Cognitive radio for next-generation wireless networks: an approach to opportunistic channel selection in ieee 802.11-based wireless mesh," *IEEE Wireless Communications*, vol. 16, no. 1, pp. 46 –54, february 2009.

[106] H. Khalife, N. Malouch, and S. Fdida, "Multihop cognitive radio networks: to route or not to route," *IEEE Networks*, pp. 20–25, August 2009.

[107] H. Harada, "A small-size software defined cognitive radio prototype," in *Proceedings of the IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, 15-18 September 2008, pp. 1–5.

[108] K. G. Shin, H. Kim, C. Cordeiro, and K. Challapali, "An experimental approach to spectrum sensing in cognitive radio networks with off-the-shelf ieee 802.11 devices," in *4th IEEE Consumer Communications and Networking Conference, CCNC 2007.*, 11-13 2007, pp. 1154 –1158.

[109] T. Yucek and H. Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications,” *IEEE Communications Surveys and Tutorials*, vol. 11, Issue No. 1, pp. 116–130, First Quarter 2009.

[110] S. Shankar, C. Cordeiro, and K. Challapali, “Spectrum agile radios: utilization and sensing architectures,” in *IEEE Int. Symposium on New Frontiers in Dynamic Spectrum Access Networks*, 2005.

[111] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu, “Knows: Kognitiv networking over white spaces,” in *2nd IEEE International Symposium on In New Frontiers in Dynamic Spectrum Access Networks (DySPAN'07)*, Dublin, Ireland, April 2007, pp. 416–427.

[112] H. Tang, “Some physical layer issues of wide-band cognitive radio systems,” in *New Frontiers in Dynamic Spectrum Access Networks, 2005. DySPAN 2005. 2005 First IEEE International Symposium on*, nov. 2005, pp. 151 –159.

[113] T. Farnham, G. Clemo, R. Haines, E. Seidel, A. Benamar, S. Billington, N. Greco, N. Drew, T. Le, B. Arram, and P. Mangold, “Ist-trust: A perspective on the reconfiguration of future mobile terminals using software download,” in *IEEE Int. Symposium on Personal, Indoor and Mobile Radio Commun*, 2000.

[114] R. Tandra and A. Sahai, “Fundamental limits on detection in low snr under noise uncertainty,” in *IEEE Int. Conf. Wireless Networks, Commun. and Mobile Computing*, 2005.

[115] R. Chen, J.-M. Park, and J. Reed, “Defense against primary user emulation attacks in cognitive radio networks,” *IEEE Journal on Selected Areas in Communications,*, vol. 26, no. 1, pp. 25 –37, jan. 2008.

[116] W.-Y. Lee and I. Akyildiz, “Optimal spectrum sensing framework for cognitive radio networks,” *Wireless Communications, IEEE Transactions on*, vol. 7, no. 10, pp. 3845 –3857, october 2008.

[117] G. Yuan, R. Grammenos, Y. Yang, and W. Wang, “Performance analysis of selective opportunistic spectrum access with traffic prediction,” *Vehicular Technology, IEEE Transactions on*, vol. 59, no. 4, pp. 1949 –1959, may 2010.

[118] A. W. Min and K. G. Shin, “Exploiting multi-channel diversity in spectrum-agile networks,” in *Proceedings of INFOCOM*, 13-18 April 2008, pp. 1921 – 1929.

[119] H. Kim and K. Shin, “Efficient discovery of spectrum opportunities with mac-layer sensing in cognitive radio networks,” *IEEE Transactions on Mobile Computing*, vol. 7, no. 5, pp. 533 –545, may 2008.

[120] ——, “Fast discovery of spectrum opportunities in cognitive radio networks,” in *3rd IEEE Symposia on New Frontiers in Dynamic Spectrum Access Networks (IEEE DySPAN)*, October, 2008., pp. 1–12.

[121] O. Mehanna, A. Sultan, and H. E. Gamal, “Cognitive mac protocols for general primary network models,” *CoRR*, vol. abs/0907.4031, 2009.

[122] A. S. Zahmati, X. Fernando, and A. Grami, “Steady-state markov chain analysis for heterogeneous cognitive radio networks,” in *Proceedings of the 33rd IEEE conference on Sarnoff*, ser. Sarnoff'10. Piscataway, NJ, USA: IEEE Press, 2010, pp. 107–111. [Online]. Available: http://portal.acm.org/citation.cfm?id=1843486.1843507

[123] B. Vujicic, N. Cackov, S. Vujicic, and L. Trajkovic, “Modeling and characterization of traffic in public safety wireless networks,” in *In Proc. of SPECTS*, 2005, pp. 214–223.

[124] “Fcc public safety spectrum.” [Online]. Available: http://www.fcc.gov/pshs/public-safety-spectrum/700-MHz/

[125] S. Geirhofer, L. Tong, and B. M. Sadler, "Dynamic spectrum access in wlan channels: Emperical model and its stochastic analysis," in *ACM TAPAS*, Aug 2006.

[126] A. Adas, "Traffic models in broadband networks," *IEEE Communications Magazine*, vol. 35, no. 7, pp. 82 –89, jul 1997.

[127] K. Sriram and W. Whitt, "Characterizing superposition arrival processes in packet multiplexers for voice and data," *Selected Areas in Communications, IEEE Journal on*, vol. 4, no. 6, pp. 833 – 846, Sept. 1986.

[128] S. L. Loukas Lazos and M. Krunz, "Spectrum opportunity-based control channel assignment in cognitive radio networks," in *6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON 2009).*, Rome, Italy, 22-26 June 2009.

[129] C. Arachchige, S. Venkatesan, and N. Mittal, "An asynchronous neighbor discovery algorithm for cognitive radio networks," in *New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008. 3rd IEEE Symposium on*, oct. 2008, pp. 1 –5.

[130] N. Mittal, S. Krishnamurthya, R. Chandrasekarana, S. Venkatesana, and Y. Zenga, "On neighbor discovery in cognitive radio networks," *Journal of Parallel and Distributed Computing*, vol. 69, issue 7, pp. 623–637, July 2009.

[131] [Online]. Available: http://stuweb.ee.mtu.edu/~ljialian/

[132] [Online]. Available: http://www.isi.edu/nsnam/ns/

[133] M. Di Felice, K. R. Chowdhury, and L. Bononi, "Modeling and performance evaluation of transmission control protocol over cognitive radio ad hoc networks," in *Proceedings of the 12th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*, ser. MSWiM '09. New York, NY, USA: ACM, 2009, pp. 4–12. [Online]. Available: http://doi.acm.org/10.1145/1641804.1641809

[134] S. Bayhan and F. Alagˆz, "Distributed channel selection in crahns: A non-selfish scheme for mitigating spectrum fragmentation," *Ad Hoc Networks*, vol. In Press, Corrected Proof, pp. –, 2011. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1570870511000941

[135] J. Riihijarvi, J. Nasreddine, and P. Mahonen, "Impact of primary user activity patterns on spatial spectrum reuse opportunities," in *European Wireless Conference (EW 2010)*, 2010.

[136] H. Goldstein, "Engineers help ngos get online after haiti quake," in *IEEE Spectrum*, 2010. [Online]. Available: http://spectrum.ieee.org/telecom/wireless/engineers-help-ngos-get-online-after-haiti-quake

[137] R. Chandra, R. Mahajan, T. Moscibroda, R. Raghavendra, and P. Bahl, "A case for adapting channel width in wireless networks," *SIGCOMM Comput. Commun. Rev.*, vol. 38, pp. 135–146, August 2008. [Online]. Available: http://doi.acm.org/10.1145/1402946.1402975

[138] L. Xu, K. Yamamototo, and S. Yoshida, "Performance comparison between channel-bonding and multi-channel csma," in *IEEE Wireless Communications and Networking Conference (WCNC 2007)*, 11-15 March 2007 2007, pp. 406–410.

[139] V. Raman and M. Caesar, "A practical approach for providing qos in multichannel ad-hoc networks using spectrum width adaptation," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, 30 2009-dec. 4 2009, pp. 1 –6.

[140] *IEEE 802.11n draft.* [Online]. Available: http://www.ieee802.org/11/Reports/tgn_update.htm

[141] *IEEE P202.22 Draft Standard for Wireless Regional Area Networks : Channel Bonding versus Channel Aggregation.*

[142] M. B. R. C. Ghosh, S. Roy and D. P. Agrawal., “Spectrum occupancy modeling and validation using real-time measurements,” in *2nd ACM Sigmobile Workshop on Cognitive Wireless Networking (CoRoNet'10) in conjunction with MobiCom 2010,*, September 2010.

[143] V. Raman and N. H. Vaidya, “Adjacent channel interference reduction in multichannel wireless networks using intelligent channel allocation,” Technical report, University of Illinois at Urbana-Champaign, August,, Tech. Rep., 2009.

[144] L. Jiao, V. Pla, and F. Li., “Analysis on channel bonding/aggregation for multi-channel cognitive radio networks,” in *European Wireless Conference (EW)*, 2010.

[145] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, “Primary users in cellular networks: A large-scale measurement study,” in *3rd IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, 2008. DySPAN 2008.*, oct. 2008, pp. 1 –11.

[146] *IEEE P202.22 (D0.1) Draft Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Bands.*

[147] *IEEE P202.22 Draft Standard for Wireless Regional Area Networks : Channel Aggregation Summary.*

[148] [Online]. Available: http://www-npa.lip6.fr/~rehmani/NS2_Code.zip

[149] F. Ge, H. Lin, A. Khajeh, J. Chiang, C. B. A. Eltawil, W. Feng, and R. Chadha, “Cognitive radio rides on the cloud,” in *Military Communications Conference (MILCOM),*, 2010.

List of figures

List of tables