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Cognitive Radio Ad-hoc Networks: A Routing Perspective

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XXV cycle

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Dedication

To my parents,

for their open-mindedness and endless support.

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List of Acronyms

CR	Cognitive Radio
DSA	Dynamic Spectrum Access
CRNs	Cognitive Radio Networks
CRAHNs	Cognitive Radio Ad-Hoc Networks
FCC	Federal Communications Commission
ITU-R	International Telecommunication Union-Radiocommunication sector
PU	Primary User
SU	Secondary User
WRANs	Wireless Regional Area Networks
RKRL	Radio Knowledge Representation Language
RF	Radio Frequency
SDR	Software-Defined Radio
CU	Cognitive User
LANs	Local Area Networks
QoS	Quality of Service
MAC	Medium Access Control
SNR	Signal-to-Noise Ratio
CCC	Common Control Channel
OLSR	Optimized Link State Routing
DSDV	Destination Sequenced Distance Vector
C-DSDV	Cognitive Destination Sequenced Distance Vector
AODV	Ad hoc On-demand Distance Vector
RREQ	Route REQuest
RREP	Route REPly
DORP	Delay oriented On-demand Routing Protocol

SOP	Spectrum OPportunity
MSCRP	Multi-hop Single-transceiver Cognitive Radio network routing Protocol
ZRP	Zone Routing Protocol
STOD-RP	Spectrum Tree based On Demand Routing Protocol
SEARCH	SpEctrum Aware Routing for Cognitive ad-Hoc networks
CRP	Cognitive Radio routing Protocol
CAODV	Cognitive Ad-hoc On-demand Distance Vector
RERR	Route ERRor
ERI-CAODV	intEr-Route dIversity CAODV
ARI-CAODV	intrA-Route dIversity CAODV
D^2CARP	Dual Diversity Cognitive Ad-hoc Routing Protocol
FHN	First Hop Node
NHN	Next Hop Node
RT	Routing Table
RERR	Route ERRor
PU-RERR	Primary User Route ERRor
Ns-2	Network simulator 2
CBR	Constant Bit Rate
UDP	User Datagram Protocol
PDR	Packet Delivery Ratio
MCAST	Mobility-aware Channel-Availability based channel Selection Technique
OPERA	Optimal Primary-aware routEquAlity
RWPM	Random WayPoint Mobility model
SPC	Single PU for Channel
MPC	Multiple PUs for Channel
CAP	Channel-Availability Probability
RMSE	Root Mean Square Error

Summary

The number of wireless devices operating on Industrial, Scientific and Medical (ISM) band increases rapidly due to the ever increasing user demand caused by the explosion of mobile applications. As a result, the unlicensed bands are getting congested which has led to the problem of spectrum scarcity in these bands. On the other hand, a large portion of the licensed bands that are reserved for public or dedicated services, such as television broadcast, remain under utilized. To solve the problem of spectrum scarcity, recently the Federal Communications Commission (FCC) proposed a new communication paradigm, referred to as Dynamic Spectrum Access (DSA), which allows the unlicensed users to opportunistically exploit the temporarily unused portions of the licensed radio spectrum, referred to as Spectrum Holes or White Spaces. If this band becomes occupied by a licensed user, referred to as Primary User (PU), the unlicensed user, referred to as Cognitive User (CU), must vacate the current band and move to another spectrum hole, avoiding the interference to PUs.

In this scenario, the Cognitive Radio (CR) has been identified as the enabling technology of the DSA paradigm due to its inherent capabilities of sensing the surrounding radio environment, learning from the interactions with the outside world and reconfiguring of its internal state. This new area of research imposes the development of Cognitive Radio Networks (CRNs) to improve spectrum efficiency. According to the infrastructure support, CRN has two classes such as the infrastructure-based CR network and the infrastructure-less CR network, referred to as Cognitive Radio Ad-Hoc Network (CRAHN). Due to the absence of the network infrastructure, CRAHN is more challenging than infrastructure-based CR network. The typical challenges are self-organizations, heterogeneity, scalability and energy constrained. The challenges become more acute because of the key distinguishing features of CRAHN, such as the

distributed multi-hop architecture, the dynamic network topology and the spectrum availability varying in time and space. These challenges require novel design techniques that address a wide range of communication problems. Therefore, CRAHN is a very active research area, which requires to develop innovative ideas to provide solutions for this above mentioned challenges and this thesis will focus on such a challenging network for further research.

The concept of CR was first proposed in 1999 by Joseph Mitola in his ground breaking dissertation. Although more than ten years have passed, the research on CRNs has mainly focused on physical and medium access issues, including the definition of accurate spectrum sensing, decision and sharing mechanisms. Only recently, the research community has focused its attention on the area of cognitive radio routing, and few works have addressed the problem of routing in CRAHNs. The routing issues on CRAHNs will be discussed in this PhD thesis since it is an emerging research area in the cognitive paradigm.

The main objective of this thesis is to address the routing problem under the challenging scenario characterized by the uncertain availability of the spectral resource. The routing problem is furthermore challenging in presence of PU mobility. To deal with this scenario, we propose to utilize jointly path and spectrum diversity in routing to assure an improved spectral efficiency. We also propose a Mobility-aware Channel-Availability based channel Selection Technique (MCAST), which performs best channel selection in terms of spectrum availability in presence of PU mobility.

The uncertain availability of the spectral resource imposes unique challenges in Cognitive Radio Networks. One of the critical issues is to counteract the performance degradation experienced by CUs due to the activity of PUs. Since the activity of PUs varies both in frequency and space domain, incorporating diversity techniques in routing can provide an efficient way to address this issue. To deal with the space-domain-dependent PU activity, we integrate path diversity on routing. It allows CUs to switch dynamically among different paths for communicating with each other in presence of space varying PU activity. On the other hand, to deal with the frequency-domain-dependent PU activity, we integrate spectrum diversity on routing. It allows CUs to switch dynamically among different channels for communicating with each other in presence of frequency varying PU activity. However, path diversity cannot counteract PU activity that varies in frequency domain, whereas spectrum diversity cannot counteract PU activity that varies in space domain. Therefore, only exploiting path or spectrum diversity cannot handle both the frequency and space varying PU activities. In order to counteract the aforementioned issue, we introduce joint path and spectrum diversity on routing that provides a promising solution in CRAHNs so that CUs can deal with both the space- and frequency- domain-dependent PU activities.

A key issue in CR networks is the design of a channel selection technique that guarantees to utilize the highest available channel in presence of the dynamic activity of PUs. Usually, the channel selection techniques that operate in this kind of network are based on the channel-availability probability. In the static PU scenario, this probability can be *a priori* known or simply estimated from the channel occupancy history. However, in the mobile PU scenario, this probability dynamically varies in time due to the changes of the PU position. In order to exploit the dynamic variation of the channel availability, we design a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) that maximizes the network performance by selecting the channel with the highest channel availability in a given temporal period.

The outline of the thesis is in the following:

Chapter 1 describes an overview of CR paradigm. More in details, we first introduce the DSA paradigm and explain the underlying reasons for its deployment, then we describe the characteristics of the CR technology and its application in wireless networks; in particular, we present an overview of CRNs, with a special focus on CRAHNs due to their challenging features which derive from the absence of the network infrastructure, by describing the comparison between classical ad-hoc and CRAHNs, spectrum management framework, and the related issues and challenges.

Chapter 2 addresses the overview of the routing in CRAHNs since the problem of routing is one of the important issues in these networks due to the uncertain availability of spectral resources. More in details, we provide a routing overview of the CRAHN by presenting the basic routing framework, challenges, classifications and the results of recent research activities. Finally, we focus on an appropriate routing approach for further study in CRAHNs.

Chapter 3 provides a promising solution for efficient use of spectrum in routing. More in details, we exploit joint path and spectrum diversity in CRAHNs, therefore, CUs can switch dynamically to different paths and spectrum bands for communicating with each other in presence of frequency- and space-varying primary user activity. This idea is adopted in a novel proposed routing protocol, referred to as Dual Diversity Cognitive Ad-hoc Routing Protocol (D^2CARP), and simulation results reveal the effectiveness of introducing joint path and spectrum diversity in routing for CRAHNs.

Chapter 4 deals with the impact of PUs mobility on channel selection in terms of spectrum availability. More in details, we propose a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST), which performs best channel selection in terms of spectrum availability in presence of PU mobility. To prove MCAST effectiveness, it is utilized in a recently proposed routing metric. Performance evaluation is conducted through simulations, and the simulation results reveal the benefits of introducing the proposed channel selection technique.

Chapter 1

Cognitive Radio Paradigm

Cognitive Radio (CR) is considered the enabling technology of the Dynamic Spectrum Access (DSA) paradigm which is envisaged to solve the current spectrum scarcity problem, thus facilitating the accommodation of new wireless services as well as providing an effective solution to the ever increasing user demand. In this chapter, we first introduce the DSA paradigm and explain the underlying reasons for its deployment, then we describe the characteristics of the CR technology and its application in wireless networks; in particular, we present an overview of CR Networks (CRNs), with a special focus on CR Ad-Hoc Networks (CRAHNs) due to their challenging features which derive from the absence of the network infrastructure, by describing the comparison between classical ad-hoc and CRAHNs, spectrum management framework, and the related issues and challenges.

1.1 Introduction

The radio spectrum is a precious resource that has a limited extension. Appropriate government agencies, such as the Federal Communications Commission (FCC) and the International Telecommunication Union-Radiocommunication sector (ITU-R), are involved in the management of this important resource. Currently, the spectrum assignment policy is based on a static paradigm where a given portion of the spectrum is assigned for the exclusive use to license holders on a long-term basis for large geographical regions. This traditional spectrum management method has many well-known advantages, such as preventing the interference between different systems through the use of adequate guard bands, and low complexity for utilizing the operating bands. Although the static spectrum assignment policy generally worked well in the past, recently it has been faced with the spectrum scarcity problem due to the ever-increasing user-demand for the radio spectrum caused by the explosion of mobile applications, which has led to a progressive saturation of this resource. On the other hand, several measurements campaigns conducted by the FCC have shown that a large part of the licensed spectrum bands which are reserved for public or dedicated services, such as television broadcasting, are in some spatial regions and for the most part of time not utilized, as illustrated in Fig. 1.1 [35], where the signal strength distribution over a large portion of the radio spectrum is shown. Thus, these studies revealed that the scarcity of the radio spectrum can be contrasted by replacing the current spectrum management policy with a more efficient dynamic access paradigm.

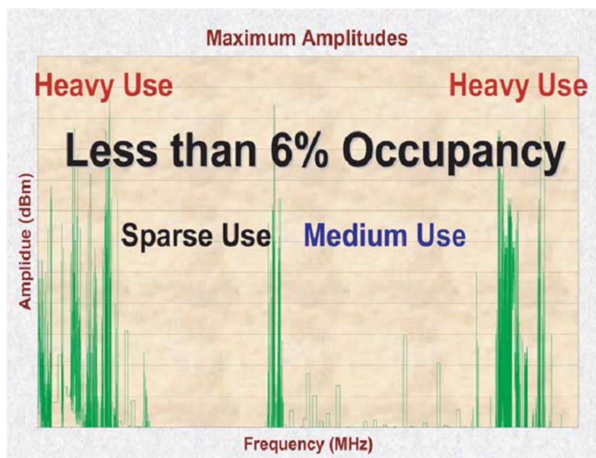


Figure 1.1: The usage of licensed spectrum.

To solve the problem of spectrum scarcity, recently the FCC [2] proposed a new communication paradigm, referred to as Dynamic Spectrum Access (DSA), which allows the unlicensed users to opportunistically exploit the temporarily unused portions of the licensed radio spectrum, referred to as Spectrum Holes or White Spaces [30], as shown in the Figure 1.2 [5]). If this band becomes occupied by a licensed user, referred to as Primary User (PU), the unlicensed user, referred to as Secondary User (SU), must vacate the current band and move to another spectrum hole, avoiding the interference to PUs.

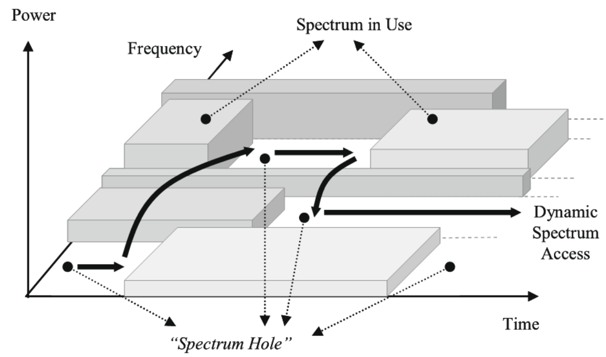


Figure 1.2: Spectrum hole concept.

In this scenario, the Cognitive Radio (CR) has been identified as the enabling technology of the DSA paradigm due to its inherent capabilities of sensing the surrounding radio environment, learning from the interactions with the outside world and reconfiguring of its internal state. For this reason, usually the DSA paradigm is also referred to as Cognitive Radio Paradigm. As an initial step towards the realization of this new paradigm, the FCC has recently approved the operation of CR devices in TV spectrum bands [1, 2]. This decision creates new opportunities for improving the efficiency of radio spectrum resources without the restrictions of the conventional static spectrum access policy, thus facilitating the accommodation of new wireless services as well as providing an effective solution to the increased user demand. Meanwhile, various standardization efforts are under development to utilize spectrum opportunities. For instance, the IEEE 802.22 Wireless Regional Area Networks (WRANs) [3] is the first standard using the spectrum holes in the TV spectrum bands with the aim to provide a last-mile wireless broadband access to users residing in rural areas.

Although the CR paradigm is envisaged to solve the spectrum scarcity problem, its implementation entails several technical challenges that are discussed in the next sections. The most fundamental challenge is to provide the CUs with proper mechanisms to efficiently and effectively exploit the spectrum holes without creating harmful interference against the PUs, which can degrade the quality of their communications.

The rest of the chapter is organized as follows. Section 1.2 describes the characteristics of CR technology, while Section 1.3 presents the general discussion about CRNs according to the network architecture. Finally, Section 1.4 provides an overview of the CRAHNs by presenting their differences with classical ad-hoc networks, spectrum management functions, and the related issues and challenges.

1.2 Cognitive Radio Technology

Cognitive Radio is the enabling technology of the DSA paradigm, which allows intelligent spectrum-aware devices to opportunistically use the spectrum holes for their communications. The concept of CR was first proposed by Joseph Mitola in his ground breaking dissertation [78], where he proposed that CR can enhance the personal wireless service by a Radio Knowledge Representation Language (RKRL). This language represents the knowledge of radio at all aspects from transmission to application scenarios in a way that supports automated reasoning about the needs of the user. Mitola's work covered interesting research subjects in multiple disciplines such as wireless communication, computer science and cognitive science. As a consequence, the radio regulatory bodies and the researchers provide some formal definitions of cognitive radio [34, 2, 30, 78]. In the following we present a couple of prominently offered definitions of cognitive radio.

FCC has defined cognitive radio as [2]: *"A cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates."*

Another definition is provided by S. Haykin in his recent popularly cited paper [30]: *"Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming radio frequency stimuli by making corresponding changes in certain operating parameters (e.g., transmit power; carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind: (i) highly reliable communication whenever and wherever needed and (ii) efficient utilization of the radio spectrum."*

From the above definitions, two main characteristics are found, such as cognitive capability and reconfigurability that make CR different from a conventional radio [31, 2, 30]. Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency bands of interest, but more sophisticated techniques such as autonomous learning and decision making are required to capture the temporal and spatial variations in the radio environment and avoid interference to other users. On the other hand, reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design. The main objective of the CR is to find the best operative internal state in order to achieve the best performance according to the perceived radio environment conditions. Fig. 1.3 [79] depicts how the cognitive radio concept can be realized through cognitive capability and reconfigurability. First, the CR acquires the information about the surrounding environment through the observation, and learns from its interaction with the external world; then, according to its knowledge, the CR makes proper decisions about the strategy to be pursued in order to achieve the best performance. Based on these decisions, the CR reconfigures its software (e.g., communication protocols) and hardware (e.g., transceiver).

In order to provide the above capabilities, CR requires a novel Radio Frequency (RF) transceiver architecture. The main components of a CR transceiver are the radio front-end and the baseband processing unit that were originally proposed for Software-Defined Radio (SDR) [21]. SDR is a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals. This technology implements radio functionalities like modulation or demodulation, signal generation, signal processing and signal coding in software instead of hardware as in conventional radio systems. The software implementation provides a higher degree of flexibility and reconfigurability and benefits including the capability to change the channel assignments, to change the provided communication services or modify the transmission parameters or communication protocols. SDR is considered a technology enabler for CR, which can learn from the environment and adapt their transmission/reception frequencies and parameters to improve spectrum utilization and communication efficiency. SDR and CR technologies are fundamental blocks to provide a more flexible approach to spectrum management in comparison to the conventional ap-

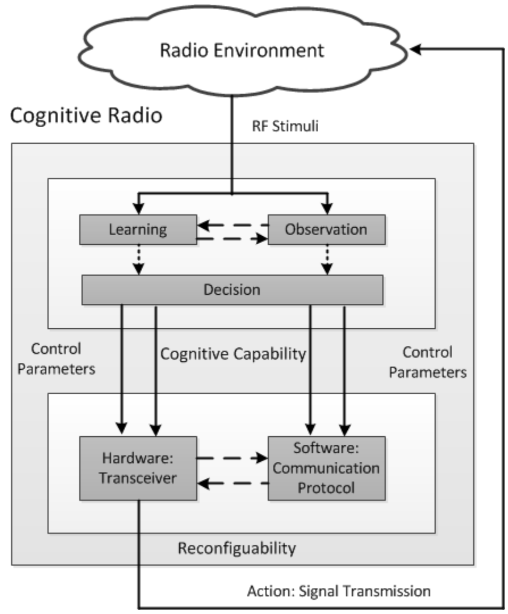


Figure 1.3: Cognitive radio concept.

proach where radio frequency spectrum bands are statically allocated by spectrum regulators. The key motivation behind SDR and CR technologies is to increase spectral utilization and to optimize the use of radio resources. In the following, we provide some challenges of SDR [16]:

- *A fundamental challenge of SDR is to provide an ideal platform to application separation, such that waveform applications can be moved from one SDR platform to be rebuilt on another one without having to change or rewrite the application;*

- *Another fundamental challenge with SDR is how to achieve sufficient computational capacity, in particular for processing wide-band high bit rate waveforms, within acceptable size and weight factors, within acceptable unit costs, and with acceptable power consumption;*

- *The flexibility benefits of SDR at the same time causes challenges in the security area, both for developers and security certification organizations;*

- *SDR poses severe challenges also in analogue RF hardware design* *and the conversion between the analogue and digital domains, particularly in wide-band implementations.*

1.3 Cognitive Radio Networks

A Cognitive Radio Network (CRN) consists of wireless nodes equipped with cognitive radios, where the radios have cognitive and reconfigurable features and the capability to detect and exploit the spectrum holes for their communications. A key issue in CRNs is the uncertainty of the spectrum availability that poses several challenges in wireless networking and communications.

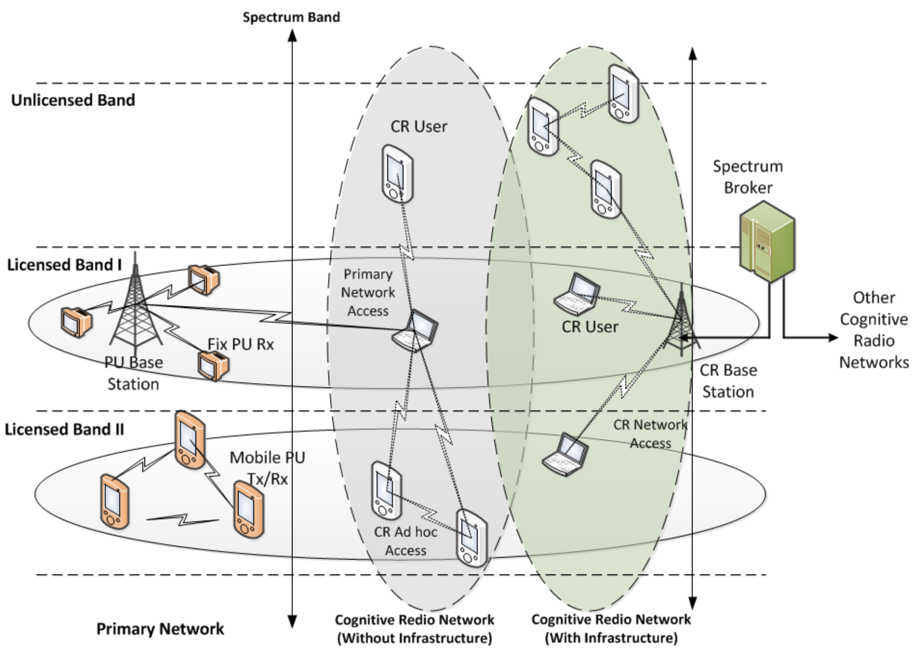


Figure 1.4: Cognitive Radio Network architecture.

The components of the CR network architecture, as shown in Fig. 1.4 [4], can be classified in two groups: the primary network and the CR network. The primary network (or licensed network) is an existing network, which has the exclusive right to operate on a certain spectrum band, for instance the common cellular and TV broadcast networks. The components of the primary network are defined in the following:

- *Primary User (PU):* It has the license to operate in a certain spectrum band. The network access is controlled by the primary base-station and must not be affected by the operations of any other unlicensed users. The primary user does not need of any modification or additional functions to coexist with the unlicensed users.

- *Primary base-station:* It is the part of the network infrastructure, whose main functionality is to coordinate the access among the primary users. In principle, the primary base-station does not have any capability for sharing the spectrum bands with the unlicensed users.

On the other hand, the CR network (also referred to as secondary network, or unlicensed network) does not have the right to operate in the licensed spectrum bands. Hence, the spectrum access is allowed only in an opportunistic manner. The components of the CR network are defined in the following:

- *Cognitive User (CU):* It is equipped with additional functionalities, e.g., the spectrum sensing, to identify and opportunistically use the spectrum holes, with the objective to satisfy the QoS requirements and guarantee the protection of the primary systems from harmful interference.

- *CR base-station:* It is the part of the CR network infrastructure, whose main object is to identify the available spectrum bands and coordinate the access among the CUs, without interfering with the communication of the primary systems.

- *Spectrum broker:* It is a central network entity that plays a role to share the spectrum resources among different CR networks. The spectrum broker can be connected to each existing network and can serve as a spectrum information manager to enable the coexistence among multiple CR networks.

According to the infrastructure support, CRN has two classes such as the infrastructure-based CR network and the infrastructure-less CR network, referred to as Cognitive Radio Ad-Hoc Network (CRAHN) [101]. The infrastructure-based CR network has a central network entity such as a base-station in cellular networks or an access point in Wireless Local Area Networks (WLANs). The CU can access to the base-station through point-to-point links. CUs, under the transmission range of the same base-station, communicate with each other through the base-station. The communications between two CUs under different base stations are routed through the backbone/core networks. The base-station may be able to execute one or multiple communication standards/protocols to fulfill different demands from CUs. A cognitive radio terminal can also access to the different kinds of communication systems through their base-station. On the other hand, the CRAHN does not have any communication infrastructure. If an CU recognizes that there are several CUs inside its transmission range, it can communicate directly with them by establishing point-to-point links, also on different spectrum bands. CUs can either communicate with each other by using the existing communication protocols on unlicensed bands (e.g. WiFi, Bluetooth) or opportunistically exploit the spectrum holes.

The comparison between infrastructure-based and ad-hoc CR networks is depicted in Fig. 1.5. In the infrastructure-based CR networks, the CR base-station has the burden to collect the spectrum information acquired locally by the CUs and elaborate them to make the decision about the bands to access without interfering with the primary networks. According to this decision, each CU reconfigures its communication parameters, as shown in Fig. 1.5 (a). On the contrary, in CRAHNs, each user needs to have all CR capabilities and is responsible for determining its actions based on the local observation, as shown in Fig. 1.5 (b). Since the CU cannot predict the influence of its actions on the entire network with its local observation, cooperation schemes are essential, where the observed information can be exchanged among CR nodes to broaden the knowledge on the network.

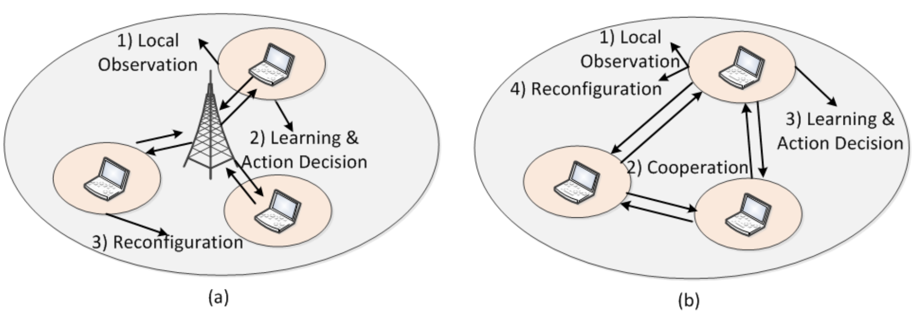


Figure 1.5: Comparison between CR capabilities for: (a) infrastructure-based CR networks, and (b) CRAHNs.

Due to the absence of the network infrastructure, CRAHN is more challenging than infrastructure-based CR networks. The typical challenges are self-organizations, heterogeneity, scalability and energy constrained [10]. The challenges become more acute because of the key distinguishing features of CRAHNs, such as the distributed multi-hop architecture, the dynamic network topology and the spectrum availability varying in time and space [5]. These challenges require novel design techniques that address a wide range of communication problems. Therefore, CRAHN is a very active research area, which requires to develop innovative ideas to provide solutions for this above mentioned challenges and this thesis will focus on such a challenging network for further research. Therefore, in the following section we discuss about CRAHNs in detail whereas for the interested readers about infrastructure-based CR Networks we refer to [6].

1.4 Cognitive Radio Ad-hoc Networks

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

1.4.1 Classical Ad-hoc Networks vs. CRAHNs

The main differences of CRAHNs compared to classical ad hoc networks are explained as follows:

- In classical ad-hoc networks, a wireless node operates on a fixed channel that remains unchanged with time. On the contrary, in CRAHNs the available spectrum bands are distributed over a wide frequency range, which vary over time and space. Thus, each user shows different spectrum availability according to the PUs activities.

- The protection of the primary system communications is the main objective in CRAHNs whereas the primary user concept is entirely missing in classical ad hoc networks.

- In classical ad hoc networks, the wireless nodes can easily exchange their topology information by periodic beacon messages on a fixed channel. However, in CRAHNs, as the licensed spectrum opportunity exists over large range of frequencies, sending beacons over all the possible channels is not feasible. Thus, CRAHNs are highly probable to have incomplete topology information, which leads to the increase of collisions among CUs as well as interference to the PUs.

- In classical ad hoc networks, a fixed spectrum band is used in multi-hop end-to-end routes, whereas it is not possible in CRAHNs due to the uncertainty of the PU activity.

- Basically, in classical ad hoc networks the end-to-end Quality of Service (QoS) requirements depends only on the traffic load, whereas, in CRAHNs, it also depends on the number of spectrum bands used in the routing path and the statistics of PUs activities.

- A routing path can be disconnected due to mobility in classical ad hoc networks, but in CRAHNs it can become unavailable also for the activities of PUs which vary in space and time.

1.4.2 Spectrum Management Framework

CR ad hoc networks impose unique challenges because of the coexistence with primary networks as well as diverse QoS requirements. Thus, new spectrum management functions are required for CRAHNs with some critical design challenges: i) interference avoidance, i.e., CRAHN should avoid interference with primary networks; ii) QoS awareness, i.e., to decide an appropriate spectrum band, CRAHN should support QoS-aware communication, considering the dynamic and heterogeneous spectrum environment; iii) seamless communication, i.e., CRAHN should provide seamless communication, regardless of the appearance of PUs. In order to adapt to the dynamic spectrum environment, the CRAHN requires to perform the spectrum-aware operations, which form a cognitive cycle, as shown in Fig 1.6 [4]. The steps of the cognitive cycle consist of four spectrum management functions: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. Due to the absence of the network infrastructure, in CRAHNs these functionalities needs to be incorporated into the classical layering protocols and implemented through the cross-layer paradigm, as shown in Fig 1.7 [5]. In the following, we investigate on these spectrum management functionalities in CRAHNs.

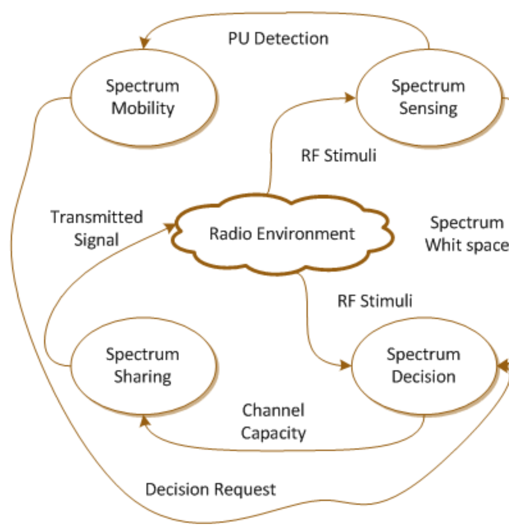


Figure 1.6: Cognitive cycle for CRAHNs.

Spectrum Sensing

Spectrum sensing is the key functionality since it enables the CUs to identify the presence of the PUs transmissions on a certain spectrum band; the objective is to efficiently exploit the spectrum holes without causing interference against the PUs. To this aim, the spectrum sensing requires the following operations [79]:

- PU Detection*: By observing and analyzing the local radio environment, CUs determine the presence of PUs transmissions, and accordingly identify the current spectrum availability. The goal is to detect the PU signal with the maximum detection probability and the minimum false alarm probability, by designing proper signal processing techniques.*

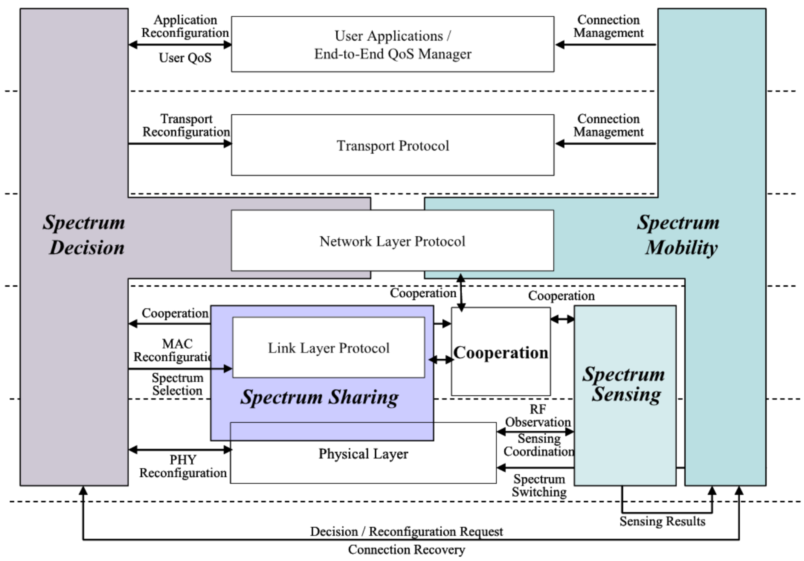


Figure 1.7: Spectrum management framework for CRAHNs.

- Cooperation*: The local observations acquired from the CUs are exchanged among each other. Through this mechanism, it is possible to exploit the spatial diversity and improve significantly the sensing accuracy.*

- Sensing Control*: The sensing operations of CUs are controlled and coordinated by a sensing controller, which considers two main issues on: i) how quickly a CU can find the available spectrum band over a wide frequency range for their transmissions [9, 11, 12], and ii) how long and how frequently a CU should sense the spectrum to achieve sufficient sensing accuracy [13, 14, 15, 17].*

Since CR networks are responsible for avoiding interference to primary networks, recent research has focused on improving sensing accuracy in PU detection. In [18], three different detection methods are investigated: matched filter detection, energy detection, and features detection. Due to the lack of strict synchronization, the CUs perform sensing operations independently of each other, leading to an adverse influence on the sensing performance. In fact, the sensing operations of a CU may interfere with the transmission of its neighboring CUs, resulting that a CU cannot distinguish the transmission from PUs and CUs. Thus, spectrum sensing is closely coupled with the spectrum sharing function and Medium Access Control (MAC) protocols.

Spectrum Decision

Each CU is able to recognize a set of unused spectrum bands after performing spectrum sensing. Then, the CU selects the best spectrum band among the available bands according to the QoS requirements of the applications, referred to as spectrum decision. It usually consists of two steps: i) each spectrum band is characterized, based not only on local observations of CUs but also statistical information of primary networks; ii) the most appropriate spectrum band is selected based on this characterization. More specifically, the following are the main operations required for spectrum decision [79]:

- Spectrum Characterization*: Based on their observation, CUs determine not only the characteristics of each available spectrum band but also the statistics of PUs activities.*
- Spectrum Selection*: CUs find the best spectrum band that satisfy the QoS requirements.*
- Reconfiguration*: CUs reconfigure their software (e.g., communication protocols) and hardware (e.g., transceiver) according to the radio environment and QoS requirements.*

CRAHNs have unique characteristics in spectrum decision due to the nature of multi-hop communication. Spectrum decision needs to consider the end-to-end route consisting of multiple hops. Furthermore, available spectrum bands in CR networks differ from one hop to the other. As a result, the connectivity is spectrum-dependent, which it makes challenging to determine the best combination of the routing path and spectrum. Thus, spectrum decision in ad hoc networks should interact with routing protocols [48, 19],

Spectrum Sharing

Spectrum sharing allows CUs to share the available spectral resource among themselves. When multiple CUs are trying to access to the spectrum, it is necessary to coordinate their transmission to prevent collisions in overlapping portions of the spectrum. Spectrum sharing includes channel and power allocations to avoid interference caused to primary networks and an intelligent packet scheduling scheme enabled by a spectrum-aware link layer along with spectrum sensing. Unlike spectrum decision, spectrum sharing mainly focuses on the resource management within the same spectrum with the following operations [79]:

- Resource Allocation*: Based on the QoS monitoring results, CUs select the proper channels (channel allocation) [20, 23] and adjust their transmission power (power control) [27, 28, 29] to achieve the QoS requirements as well as resource fairness.*

- Spectrum Access*: It enables multiple CUs to share the spectrum resources by determining who will access the channel or when a user may access the channel [24, 25, 26].*

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

Spectrum Mobility

If the PU transmission occurs during the communication of a CU then it has to vacant the spectrum immediately. However, the CU communication needs to be continued by switching to another unused spectrum band, referred to as spectrum mobility. The main operations required for spectrum mobility in the CRAHN are described in the following [79]:

- Spectrum Handoff*: The CU switches the communication to another spectrum band and reconfigures the communication parameters for the RF front-end (e.g. operating frequency, modulation type).*

- Connection Management*: The CU sustains the QoS or minimizes the quality degradation experienced during the spectrum switching through the interaction of the layering protocols.*

Spectrum mobility in CRAHN mainly focuses on link failure on the end-to-end route. Compared to the infrastructure-based network, the

CRAHN has more dynamic and complicated topology dependent on both spectrum and user mobilities. Indeed, CRAHN uses routing protocol to recover the link failure on its end-to-end route, but cannot manage the mobility events as efficiently as the infrastructure-based networks due to the lack of the central entity as well as more complicated topology. For these reasons, it is much more difficult to design spectrum mobility in CRAHNs compared to the infrastructure-based networks.

1.4.3 Issues and Challenges of CRAHNs

In this section, we discuss several issues and challenges [5, 35, 36] that should be investigated for the development of CRAHNs in different aspects, such as spectrum sensing, spectrum decision, spectrum sharing, spectrum mobility, control channel management and routing.

- Coordination of asynchronous sensing*: Due to the independent and asynchronous sensing, and transmission schedules in CRAHNs, a CU cannot distinguish the transmission of CUs and PUs rather only can detect the presence of a transmission. The transmission of CUs detected during sensing operations causes false alarm in spectrum sensing. Thus, how to coordinate the sensing task among the CUs to reduce these false alarms is one of the most important issues in spectrum sensing.*

- Optimization of cooperative sensing*: Cooperative sensing introduces another crucial issue that it improves the accuracy of sensing but also increases the network traffic. Moreover, it results in higher latency in collecting cooperative sensing information due to channel contention and packet re-transmission. Therefore, it is necessary to design an optimum and efficient sensing strategy by taking in account of these issues in CRAHNs.*

- Spectrum-efficient sensing*: The sensing time directly affects the transmission performance of CUs. The greater is the sensing time, the higher is the detection probability, but the lower is the transmission time. As a result, balancing spectrum efficiency and sensing accuracy is an important issue. Thus, a novel spectrum sensing approach should be developed such that the sensing time is minimized within a given sensing accuracy.*

- Decision model*: The spectrum band can be classified based on the environmental parameters e.g., Signal-to-Noise Ratio (SNR), QoS requirements and the statistical information of PU activities. Therefore, a decision model is necessary that considers these features and selects the optimum channel from the available channel list for CU communication.*

- Distributing topology information*: It is an important issue for sharing the spectrum bands among the CUs. In CRAHNs, it is difficult for several reasons: PUs activities are time varying on the spectrum bands; channel availability of CU varies with time; no dedicated common control channel for interchanging signalling information with each other. Therefore, a suitable Medium Access Control (MAC) protocol needs to be designed by accounting of these challenges.*

- Switching delay management*: The spectrum switching delay is closely related with hardware, algorithm development for spectrums sensing, spectrum decision, link layer and routing. Thus, it is necessary to design spectrum mobility in a cross-layer approach to decrease the operational overhead among each functionalities and to get a faster switching time.*

- Flexible spectrum handoff framework*: There are two different strategies of spectrum handoff, such as reactive and proactive spectrum handoffs. In the first approach, CUs switch the spectrum before PUs appear based on the prediction of PU activities, which significantly reduces the spectrum switching time. Again, energy constrained devices, e.g. sensors or mobile devices, need a reactive spectrum switching strategy. Therefore, it is necessary to develop a flexible spectrum handoff framework to exploit different switching strategies.*

- Routing Algorithms*: In traditional ad-hoc network, all nodes communicate each other through pre-allocated spectrum band. However, in CRAHNs, there may be no such pre-allocated spectrum that can be used by every node at any time. Moreover, the spectrum band that can be used for communication may vary with time and location. Therefore, designing a routing algorithm for CRAHNs is a challenging task. Routing in CRAHNs should consider spec-*

trum decision, PU awareness, QoS, spectrum handoff, and ensure satisfying network performance such as high network capacity and throughput, short latency and low packet loss.

Chapter 2

Routing in Cognitive Radio Ad-Hoc Networks

The problem of routing is one of the important issues in Cognitive Radio Ad-Hoc Networks (CRAHNs) due to the uncertain availability of spectral resources. In this chapter, we provide a routing overview of the CRAHN by presenting the basic routing framework, challenges, classifications and the results of recent research activities. Finally, we focus on an appropriate routing approach for further study in CRAHNs.

2.1 Introduction

The Cognitive Radio paradigm has been recognized in 1999 [77] as an effective way to deal with bandwidth scarcity and/or inefficient usage. Although more than ten years have passed, the research on cognitive radio networks (CRNs) has mainly focused on physical and medium access issues [7, 61], including the definition of effective spectrum sensing, decision and sharing mechanisms. Only recently, the research community has focused its attention on the area of cognitive radio routing, and few works have addressed the problem of routing in CRAHNs [61].

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

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

2.2 Network layer for CRAHNs

In the network layer of CRAHNs, for achieving optimum solution it is necessary to take in account both the results of the selection of the transmission bands and the routing path. Each CU has limited local information and there is no reliable signalling scheme which allows the CUs to completely share their topology information each other. The sudden appearance of a PU in the CU range may cause the unavailability of certain channels which the CU was utilizing. Therefore, it is necessary to perform a local change in the existing routes. In such a situation, the routing layer can provide the following solutions [5]: i) Circumventing the affected region, increasing however the path length and, consequently, the end-to-end delay; ii) Changing the spectrum band to keep the routing path constant, giving rise to a one-time channel switching delay. Moreover CU mobility may cause frequent route outages and repeating the entire route discovery process is costly in terms of resource usage. It is worthwhile to note that CUs may also move into active PU region, thus necessitating immediate route management procedures.

2.2.1 Basic framework

A general routing framework [5] is presented in Fig. 2.1 that consists of several blocks such as routing information, QoS evaluation, learning, decision and route establishment block. Routing decision is performed with the interaction of these blocks whose descriptions are provided in the following:

- Routing Information Block*: In classical ad hoc routing, this block keeps limited information i.e., only next hop information. However, in CRAHNs, this block keeps full information such as channel quality, transmission rate, modulation and other parameters that are unique to each link. Channel switching involves a finite delay, which affects the final end-to-end performance [47]. The choice of*

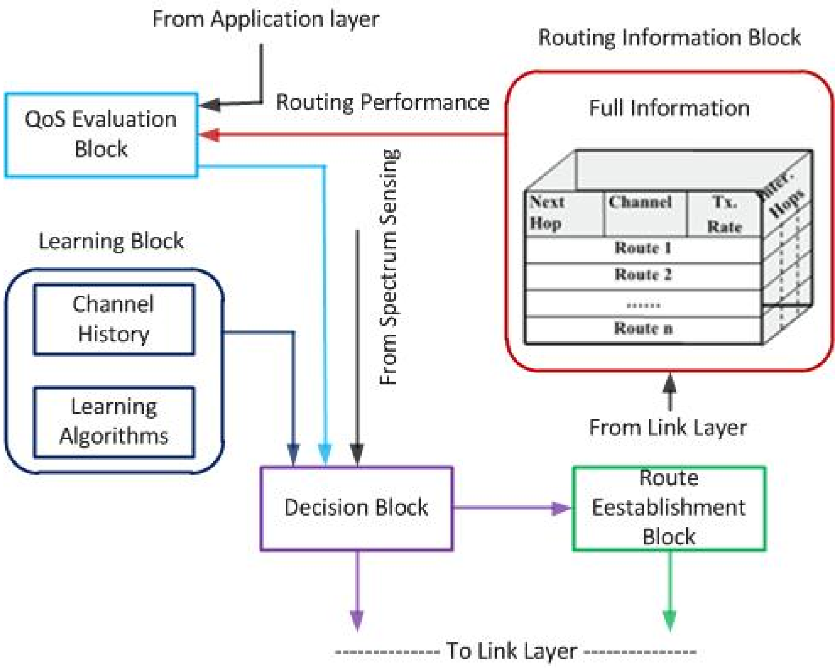


Figure 2.1: Routing framework for CRAHNs.

channels may be performed in order to minimize the number of channel switches along the path based on the full routing information.

- QoS Evaluation Block*: This block receives the service requirements from the application layer and measures how close the current performance of the routing algorithm is to these requirements.*

- Learning Block*: Networks evolve towards the self-learning and environment aware paradigm, as a consequence the routing framework should incorporate a learning block. By accounting for the channel history, this block tunes the working of the routing layer over time and helps the decision block to make progressively better channel and path switching decisions.*

- Decision Block*: Accounting for the sensing information, the results of QoS evaluation block and learning block, decision block sort out to alter an existing route or switch a channel or keep continuing* *the existing one.*

- Route establishment block*: Finally, this block establishes a route from source to destination with the help of previous block information for achieving the best (according to a selected metric) routing performance.*

2.3 Routing in CRAHNs

CRAHN is an emerging multi-hop wireless networking technology where CUs are able to reconfigure their transmission or reception parameters based on the environmental changes. Routing problem in CRAHNs has similarities with routing in multi-channel, multi-hop ad hoc networks, but with the additional challenges to deal with the dynamic behavior of the PUs, and their effects on changing spectrum opportunities availability of CUs. In the following we underline some design challenges of routing in this networks [37]:

- Dynamicity of channel availability*: The availability of the channel for data transmission is dynamic in CRAHNs, because of the PUs activities and mobility scenarios. As a result, routing has to face frequent link failure that can cause higher routing overhead.*

- Diversity of operating channels*: The source CU is connected with the destination CU through the several intermediate CUs in CRAHNs. Channels with different intermediate frequencies provide different levels of data rates and transmission ranges, which affect route selection [38]. Therefore, QoS provisioning is challenging because intermediate CUs may switch to a new operating channel due to dynamicity of channel availability.*

- Lack of a fixed Common Control Channel (CCC)*: The CUs exchange control and data packets through control and data channel, respectively. Resulting from the dynamicity of channel availability, the assumption of fixed CCC will not be reasonable [46, 39, 40, 41]. As a consequence, designing a routing scheme in CRAHNs, it is necessary to consider flexible control channel to provide feasibility of implementation.*

- Integration of routing with channel decision*: Channel decision in CRAHNs should interact with routing protocols caused by the uncertainty of PU activities as well as the mobility activities [5, 46, 39, 48, 45].*

- Minimizing delay*: Routing schemes should cater for minimizing the delays due to the channel switching, medium access, queueing and backoff since these delays affect the routing performance [61]. Switching delay is defined as the delay caused by switching among frequency bands. Medium access delay depends on the MAC access scheme used in a given frequency band. Backoff delay is caused by multi-flow interference within a frequency band. Queueing delay is based on the output transmission capacity of a node on a given frequency band.*

- Heterogeneity of CUs*: A CRAHN may consist of CUs with different capabilities such as transmission power and processing speed [63]. For instance, an intermediate CU with limited capability may become a bottleneck and this degrades the end-to-end performance. As a consequence, routing schemes should be aware of the heterogeneity of CUs.*

Having these goals in mind, numerous routing protocols have been proposed in the last years, which can be classified according to the traditional way in four major categories: proactive, reactive, hybrid and special features routing, as depicted in Fig. 2.2. In the following, for each class we first describe the main characteristics and then present some illustrative examples along with an high level description of each example. Finally, the summary of routing protocols in CRAHNs are explained in Table 2.1.

2.3.1 Proactive Approach

In proactive approach, each CU source node exchanges routing packets with neighbor nodes, and keeps track of each route in a routing table. Optimized Link State Routing (OLSR) [64] is an example of a traditional proactive routing scheme. The main advantage of proactive routing is that the routes are available and also updated periodically. Therefore, CU can get route information when needed by simply looking

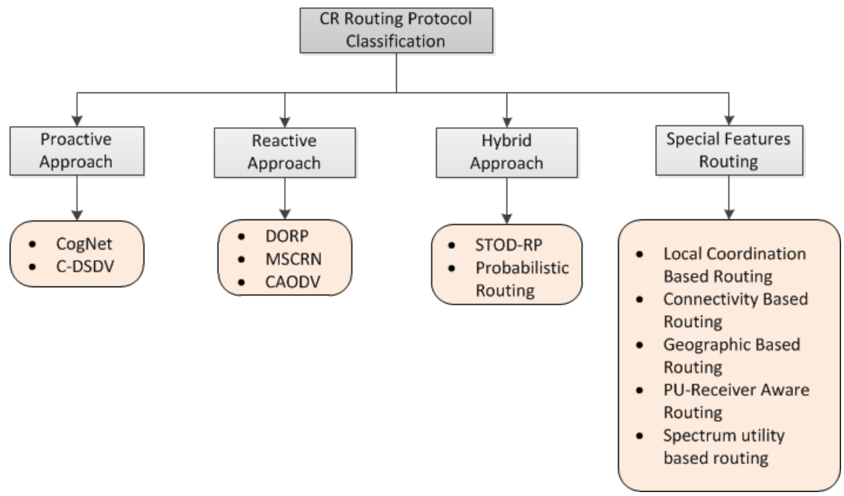


Figure 2.2: Routing Classification in CRAHNs.

for the destination in the routing table, which helps to reduce end-to-end delay. On the other hand, the main issue of proactive routing is related with the bandwidth consumption and network overhead. Large network size and high CU mobility may introduce large network overhead. There are several proactive routing protocols available in literature [40, 93, 42, 95, 41, 44, 66].

In [66], the authors propose a proactive routing protocol for CRAHNs, referred to as C-DSDV, which is the enhancement version of Destination Sequenced Distance Vector (DSDV) protocol [68]. The routing and the channel allocation are the two main challenges that are considered in C-DSDV. Each CU in the network maintains a routing table with all possible destinations, and the number of routing hops to each destination is recorded. This information is available for all time and also periodically updated. New route broadcasts contain the destination address, sequence number (for getting fresh broadcast) and the number of hops to reach the destination. The sequence number is unique for each broadcast. The nodes will transmit the updates immediately using control channel if new information arrives or a change in the topology or a switch in the channel.

In [41], the authors propose a path-centric spectrum assignment framework (Cog-Net), which maximizes the network throughput. The routing scheme addresses some challenges, such as integration of route discovery with channel decision to minimize the switching delay. The objective of switching channels in a multi-channel wireless network is to reduce the packet collision among neighboring nodes using the same channel and thus increasing the throughput. However, using multiple channels is not always beneficial. For example, when the traffic volume traversing a node is light, the collision should be low and thus switching the radio of this node among different channels may not be beneficial because the channel switching overhead may result in lower throughput than using a common channel. On the other hand, when the traffic volume is high, switching the radio between channels is clearly beneficial. This work poses a path centric channel assignment technique that considers both the issues. More in details, each CU constructs a multi-layer graph to model the entire network in order to facilitate route discovery and channel selection along the route. Each layer represents connections using a single channel; while each node in the graph represents a single CU node. The edges of the layered graph can be of three types: access, horizontal, and vertical. We can explain it with an example; as shown in Fig. 2.3 (a), a simple network topology with four nodes is able to be tuned to channels ch1 and ch2. The corresponding layered graph architecture is shown in Fig. 2.3 (b). The edges laying on the two horizontal planes representing the two available channels (ch1, ch2) are horizontal edges, dashed vertical edges are vertical edges, and small dashed ones represent access edges. Each horizontal edge represents a connection within a layer using a particular channel. Each vertical edge represents a channel switch, and so the number of vertical edges represents the number of operating channels. Subsequently, a traditional routing algorithm, such as Dijkstra's algorithm [65], is used to find the least cost route, which is computed using the horizontal and vertical edges. As part of the cost computation, a horizontal edge represents the traffic volume of a link and CU to CU interference, while a vertical edge represents switching delay between channels. Lastly, channel selection is invoked on the selected route to achieve a balanced tradeoff between switching delay and traffic loads.

2.3.2 Reactive Approach

In reactive approach, a CU source node establishes a route with destination when it is needed. Generally, a CU floods the network with Route REQuest (RREQ) packets. After receiving the RREQ, the CU

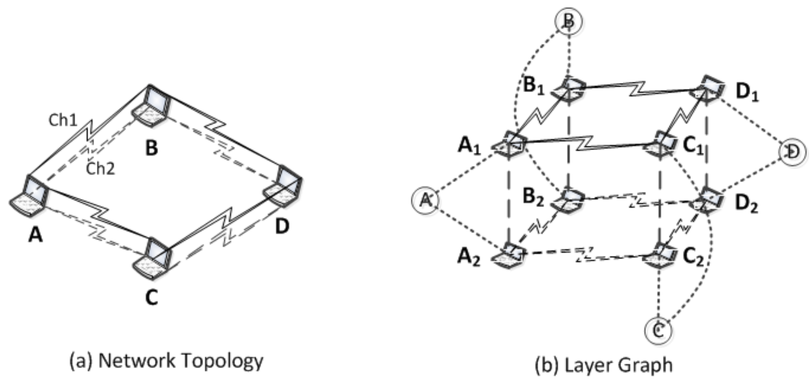


Figure 2.3: Layered-graph creation.

destination node responds with a Route REPly (RREP) packet. Ad hoc On-demand Distance Vector (AODV) [69] is an example of a traditional reactive routing approach. The benefit of reactive routing is a reduction of the bandwidth consumption and network overhead, with respect to proactive routing, particularly in network with moderate data session rate or high level of node mobility. The drawbacks are the presence of a route acquisition latency and a notable overhead in the case of route discovery process. There are several reactive routing protocols available in literature [48]-[60].

In [48], the authors propose a Delay oriented On-demand Routing Protocol (DORP) that combines several delay metrics (switching delay, backoff delay and queuing delay, as described in Section 2.3) to efficiently select minimum end-to-end delay route. DORP evaluates the cumulative delay of a path using both path and node delay. The path delay takes into account the switching delay and backoff delay caused by the path and depends on the frequency bands assigned to all nodes along the path. The node delay is caused by existing flows at relaying node and it depends on the number and frequency bands of traversing flows. DORP works similar to AODV [69] routing protocol. In the route discovery phase, source CU sends RREQ when it wants to discover a route towards a destination CU, when an intermediate CU receives the RREQ it checks its current Spectrum OPportunity (SOP) and if it has intersection with the closest SOP, it attaches current SOP to RREQ and forward to next CUs. However, if the RREQ is received by the destination CU, it chooses frequency band from intersection of SOPs with minimum node delay, encapsulates this choice into RREP and send it back to the source. When an intermediate CU receives the RREP, it chooses frequency band from intersection of SOPs with minimum node and path delay, where path delay is calculated with nodes from source CU to the destination CU, and encapsulates the spectrum choice into the RREP and sends it back to the source CU. Finally the source CU starts to send data packets.

The Multi-hop Single-transceiver Cognitive Radio network routing Protocol (MSCRP) is proposed in [49]. This routing scheme addresses some challenges, which are dynamicity of channel availability, lack of a fixed common control channel and minimization the channel switching delay and backoff delay. A mechanism is designed to interchange control information of routing protocol among CUs without a common control channel. This mechanism is embedded in the routing framework. It maximizes the throughput of each flow through achieving a balanced tradeoff between the channel switching delay and backoff delay. Therefore, the network throughput improves because the proposed channel assignment algorithm can balance the channel load. Based on a delay analysis, the enhancement of channel utilization is achieved. After a route to the destination has been discovered, channel selection is performed. An intermediate CU node is aware of the channel selection, thus it selects a channel for its link towards the source CU that increases the available time for data transmission in order to reduce switching delay. Additionally, the channel selection also limits the opportunity of channel switching to a single CU among its CU neighbors in order to counteract the deafness problem. Allowing nodes to switch channels can lead to deafness problem, in which two CUs cannot communicate because they are listening on different channels.

2.3.3 Hybrid Approach

The hybrid approach combines the characteristics of both the proactive and reactive routing schemes. It achieves a balanced performance tradeoff between proactive and reactive routing schemes in various network scenarios with different requirements. The Zone Routing Protocol (ZRP) [70] is an example of a traditional hybrid routing scheme. There are several hybrid routing protocols available in literature [39, 71, 62].

In [39], the authors propose the Spectrum Tree based On Demand Routing Protocol (STOD-RP) in order to simplify channel and route selection. This routing scheme addresses some challenges, such as the dynamicity of channel availability, lack of fixed CCC and integration of route discovery with channel decision. This hybrid scheme is comprised of proactive and reactive routings. Proactive routing is performed to maintain an intra-channel routing tree i.e., a single channel is common for the entire path, as shown in Fig. 2.4 (a). Since a CU may be an overlapping CU (namely, a CU that can access multiple channels), it may become to different channel routing trees. Proactive routing is also applied to establish routes across different routing trees, referred to as inter-channel routing trees if there is only a single overlapping CU that can serve as an intermediate CU for different routing trees, as shown in Fig. 2.4 (b). Otherwise, if there are several overlapping CUs, reactive routing is performed by the overlapping CU to establish a route between the CU source and destination using a routing metric, as shown in Fig. 2.4 (c). Additionally, a CU may use on-demand routing to establish routes within a routing tree using a single channel, as shown in Fig. 2.4 (a). The routing metric is based on end-to-end delay and PU utilization level. As for route recovery, two heuristic mechanisms are proposed to maintain the intra-channel and inter-channel routing trees in response to link failure and CU mobility.

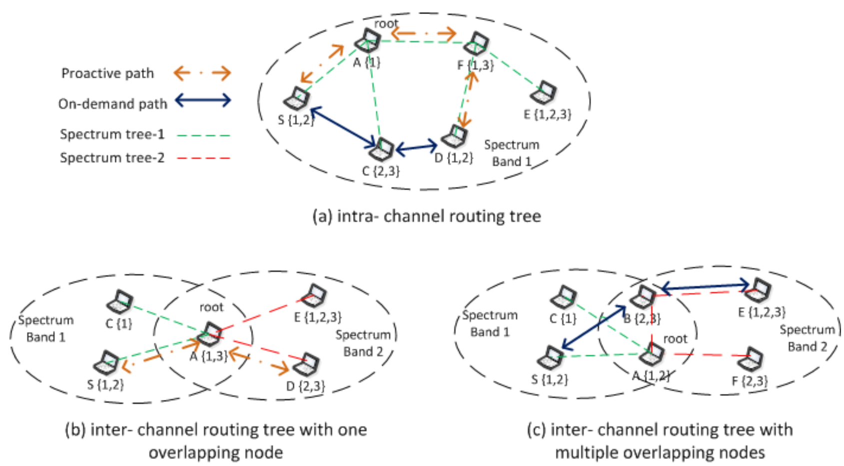


Figure 2.4: Examples of spectrum-tree.

In [71], the authors propose a joint routing and channel selection scheme to fulfill bandwidth requirements of flows. This routing scheme addresses some challenges such as dynamicity of channel availability and integration of route discovery with channel decision. The link weights are calculated based on the interference from the PUs, the received signal strength, and the PU occupancy rate on all the channels at the given link. The CR users calculate an expected delay from themselves to the possible destinations, and use a classical distance-vector algorithm, such as Bellman Ford or Dijkstra, to decide on the optimal path.

2.3.4 Special Features Routing

The following routing protocols have been proposed in literature for CRAHNs which exhibit special features.

Local Coordination Based Routing

The local coordination [72] is a sort of enhancement scheme that is applied on intersecting node (receiving multiple flow from different neighbors) on a path. This node decides whether to accommodate an incoming new flow or to redirect it to its neighbors to relief local workload. This local coordination includes the operation of exchanging cost evaluation information with neighborhood and the redirection of the flow to a selected neighbor of the intersecting node. Both routing and spectrum assignment are based on the adoption of an on-demand protocol that is a variation of the AODV. Fig. 2.5 shows the implementation flowchart of the local coordination scheme. During the route setup process, local state information are piggybacked into the route request packets and delivered to the destination node. The protocol operation starts with the source node broadcasting of a RREQ message. As it is being forwarded, intermediate nodes add their own spectrum opportunities (SOPs), a list of currently available and unavailable channels through the RREQ messages. Once a RREQ message reaches the destination node, it estimates a set of cumulative delays based on possible available local frequency bands using a proposed metric. Once it chooses the best possible frequency band according to the minimum delay, it sends a Route Reply (RREP) message on the reverse path of the RREQ packet. All nodes along the reverse path process the RREP packet following the procedures of the destination. The similarities with the AODV protocols end at this point. The protocol envisions the possibility of changing the routing decisions as the RREP is forwarded along the reverse path. The rationale behind this lies in the fact that nodes carrying more than one flow may have to switch between two or more frequency bands, which

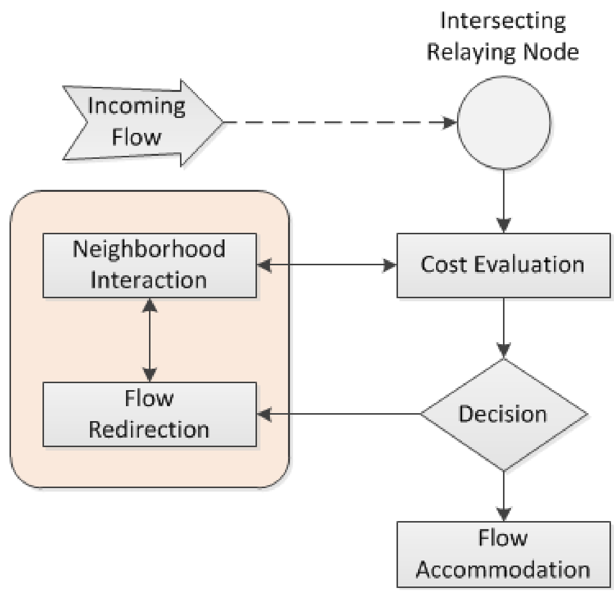


Figure 2.5: Flowchart of local coordination scheme.

incurs a larger delay. Therefore, when a RREP packet is received by an intersection node, it checks its own neighbors to see if there is a better alternative to carry the flow in question. If any of the neighbors of the node that processes the RREP can provide a better delay, then the flow is routed over this new node and the previous hop is also notified of this change.

Connectivity Based Routing

Connectivity in CRAHNs is significantly affected by both PU activity and mobility scenarios. In this view, a new distributed protocol referred to as Gymkhana is proposed in [73] which is aware of the degree of connectivity of possible paths towards the destination and to routes the information across paths. The routing paths avoid the network zones that do not guarantee stable and high connectivity.

To discover all possible paths towards the destination node, a source node broadcasts a route request packet across the network. The destination uses the information contained in the received route request to run the Gymkhana algorithm to classify paths on the basis of their connectivity and to select one path among all discovered paths. At the destination node, contents of the route request are processed in two steps: i) Virtual graph is formed for all paths; ii) Calculation of the eigen values of the Laplacian of the virtual graph which is used to evaluate the connectivity of a path. The proposed mathematical model evaluates the connectivity of the different paths by taking into account the PUs behavior, the cost of channel switching and the hop count.

Geographic Based Routing

The SpEctrum Aware Routing for Cognitive ad-Hoc networks (SEARCH) [74] is based on the geographic forwarding principles. According to the proposed protocol routing and channel selection decisions are performed by avoiding PU active regions. The key functionality in the proposed scheme is to evaluate when the coverage region of the PU should be circumvented, and when changing the channel is the preferred option. First, the shortest paths to the destination, based on geographic forwarding and consideration of the PU activity, are identified on each channel. The destination node then combines these paths by choosing the channel switching locations, with the aim to minimize the number of hops to the destination.

In the route setup phase, a route request (RREQ) is transmitted by the source on each channel that is not affected by the PU activity at its current location. It gets forwarded by intermediate hops till it reaches the destination node. SEARCH operates in two modes such as Greedy Forwarding and PU Avoidance. Greedy geographic forwarding can decide which of the candidate forwarders of the RREQ should be chosen as the next hop to minimize the distance to the destination node. In the PU avoidance phase, the RREQ starts circumventing around the affected region. Finally, the routes on the individual channels are combined at the destination by the joint channel-path optimization algorithm.

PU-Receiver Aware Routing

The PU-Receiver aware routing protocol for CRAHNs is proposed in [75], referred to as Cognitive Radio routing Protocol (CRP). The metrics that are considered during the route setup stage are (1) the probability of bandwidth availability, (2) the variance in the number of bits sent over the link, (3) the spectrum propagation characteristics, (4) the PU receiver protection, and finally, (5) the spectrum sensing consideration, i.e., CUs undertake spectrum sensing at periodic intervals to maintain an updated information regarding the spectrum occupancy. The route setup performs two stages. In the first stage (spectrum selection stage), each CU identifies the best spectrum band and the preferred channels within that band, this is done using many unique CR metrics (mentioned before) which are weighted appropriately in an optimization framework for choosing the spectrum. An optimization function is developed for each class of CR route, which also serves as a measure of the initiative displayed by the CU for participating in the route. In the second stage (next hop selection stage), the candidate CUs rank themselves depending on the choice of the spectrum, and the local network and physical conditions; these ranks determine which CUs take the initiative in the subsequent route information, and this initiative is mapped to a delay function for forwarding the RREQ message, so the preferred users broadcast the RREQ earlier. The destination chooses the final route that best meets the goals of the desired routing class by a route reply (RREP).

Spectrum utility based routing

The spectrum utility based routing for achieving high throughput efficiency is proposed [76]. The authors introduce a spectrum utility for the generic link (i, j) defined as the maximum differential backlog between node i and node j:

$$U_{i,j} = \max_{s} c_{i,j}(Q_i^{s^*} - Q_j^{s^*}) \tag{2.1}$$

where $c_{i,j}$ is the achievable capacity for link (i, j), $Q_i^{s^*}$ is the current backlog of packets at node i for the session (packet flow) s and s^* is the session with the highest differential backlog. The generic node i performs the following actions:

- *it periodically searches for the list of potential next-hops for session* $s\{n_1, n_2, ..., n_N\}$*;*
- *it calculates the capacity (*$c_{i,j}$*, where* $j \in \{n_1, n_2, ..., n_N\}$*) over the links towards all the potential neighbors; more specifically, given the current spectrum condition, each CU runs a distributed decision algorithm to decide which spectrum mini-bands should be used for the access and which power level to be used throughout the aforementioned spectrum bands;*

- *it chooses the actual next hop, j^*, that maximizes the spectrum utility, that is:*

$$(s^*, j^*) = \arg\max_{j,s}(U^s_{i,j}) \tag{2.2}$$

The proposed routing protocol is further coupled with a cooperative sensing technique which leverages both physical sensing information on spectrum occupancy and virtual information contained in signalling packets exchanged by secondary nodes. The exchange of additional virtual information is performed through a common control channel and is used by the local spectrum/power allocation algorithm.

2.4 Suitable Routing Approach in CRAHNs

. CRAHN is a category of cognitive radio networks with the absence of either infrastructures or centralized entities. Without any centralized point, CUs have to cooperate with other CUs in ad-hoc manners to exchange information and obtain necessary knowledge, such as network topology and the presence of PUs. The routing protocol for CRAHNs should satisfy the requirements of both cognitive radio networks and ad-hoc networks. The main concern of cognitive radio communication by CUs is to avoid impeding the PUs transmission. Similar to the ad-hoc networks, CRAHN is a temporary network where the CUs are mobile and PUs are static and/or mobile. Due to the unpredictable nature of ad-hoc network, reactive routing performs better than other approaches in this network [67]. Moreover, the activity of PUs is unpredictable. By analyzing these issues, we can consider that reactive routing approach will be also the suitable choice for CRAHNs. Furthermore, most of the routing solutions for CRAHNs in literature are provided through reactive approach [48, 45, 49, 46, 50, 52, 53, 56, 81].

AODV is a prominent routing protocol that performs better in traditional ad-hoc scenario compared to other reactive protocols [82]. Therefore, in this thesis we consider Cognitive Ad-hoc On-demand Distance Vector (CAODV) [83] protocol, which is based on AODV, for further study in CRAHNs. The details of this routing are described in the following.

2.4.1 Cognitive Ad-Hoc On-Demand Distance Vector

The Cognitive Ad-hoc On-demand Distance Vector (CAODV) is a reactive routing protocol based on the AODV protocol and designed for operating in mobile CRAHNs. As a consequence, CAODV inherits some AODV features: the route setup is based on an expanding ring search mechanism and it exploits route request (RREQ) and route reply (RREP) packets. Moreover, the route maintenance uses Route ERRor (RERR) packets for reacting to topology changes due to CU mobility or wireless propagation instability.

The similarities end at this point. Differently from AODV, the CUs should be able to exchange the control packets through the licensed spectrum without causing harmful interferences to the primary users also in presence of imperfect spectrum sensing mechanisms. Although cooperative approaches at the physical layer are recognized as a viable solution to improve the reliability of the spectrum sensing, in CAODV the authors do not make any assumption about the adopted sensing mechanism and, therefore, a mechanism to enforce the PU activity detection at the network layer is required.

Moreover, the CUs should be able to exploit the spectrum diversity provided by the cognitive radio paradigm without causing excessive overhead for route formation. To this aim, the authors exploit two different approaches for spectrum diversity utilization: the inter-route diversity and the intra-route one. Finally, the route maintenance process should be able to locally handle the changes in spectrum availability due to PU arrival or departure, avoiding so to waste the bandwidth with a new route setup process.

In the following, both the versions of CAODV are presented, highlighting the main differences between the two approaches for spectrum diversity utilization.

Inter-route diversity CAODV

The route setup process of intEr-Route dIversity CAODV (ERI-CAODV) has been designed to exploit inter-route diversity by imposing that: (i) different routes evolve through different channels; (ii) each route evolves through the same channel. Although such a design principle is suboptimal since it requires the availability of a channel idle (i.e. free from PU activity) in the whole region traversed by the route, it allows

ERI-CAODV to exploit spatial diversity by discovering multiple routes (at most l as the number of channels) through different intermediate CUs.

More in detail, when an intermediate CU receives a route request (RREQ) packet through an idle channel, say channel i, it sets up a reverse route toward the source through the same channel. If the CU can supply a valid route for the desired destination, then it sends a unicast route reply (RREP) packet back to the sender through the reverse route. Otherwise, it re-broadcasts the received route request through the same channel. If an additional request for the same pair source-destination is received by the same CU through the same channel, it is processed only if it refers to a newer route discovery session or to a better reverse route than the one stored in the routing table. Otherwise, it is simply discarded.

On the other hand, when an intermediate CU receives the first route reply through an idle channel, say channel i, it sets up a forward route through the same channel toward the destination and it forwards a copy of the reply along the reverse route stored in its routing table (through the same channel). If an additional reply for the same pair source-destination is received by the same CU through the same channel, the CU processes such a reply only if it refers to a newer route discovery session or to a better forward route than the one stored in the routing table.

Intra-route diversity CAODV

The route setup process of intrA-Route dIversity CAODV (ARI-CAODV) has been designed to allow CUs to exploit intra-route spectrum diversity by relaxing the constraint that the same channel is available in the whole region traversed by the route. The drawback of the intra-routing diversity is that it cannot exploit spatial diversity as it made for the IRA-CAODV protocol to avoid route loop.

When an intermediate CU receives the first route request through an idle channel, it sets up a reverse route through the same channel and it broadcasts a copy of the RREQ packet through each available channel. As a consequence and differently from ERI-CAODV, a further route request on a different channel will be broadcasted only if it refers to newer discovery session or better reverse route. This mechanism allows an intermediate CU to try to establish several links toward the next hop by sending a route request through each idle channel.

Anew class of packets, the PU-RREQ packets, are used when the local spectrum sensing mechanism recognizes that a channel previously used by a PU has been released. If it happens, the sensing node locally broadcasts a PU-RREQ so that it can benefit from this spectrum availability by establishing for each active route a link on that channel.

Similarly to route request management, when an intermediate CU receives the first route reply, it sets up a forward route through the same channel and it forwards a copy of the reply along each channel for which a reverse path has been set in the routing table. A further route request on a different channel will be re-broadcasted only if it refers to newer discovery session or better reverse route.

This mechanism allows the intermediate CU: (i) to establish a forward link on a channel only after the reception of a reply on such a channel, i.e. to establish a forward link only for bidirectional idle channels; (ii) to forward a reply for establishing a reverse link for each channel through which a request has been received, independently from the reception of a reply on such a channel. In such a way, the protocol is able to maximize the spectrum utilization for a given route, by establishing a link on each symmetric channel free from PU activity.

Protocol	Approach	No. of TxRx	Fixed CCC	Route Metric	True Cross-layer	Advantage	Disadvantage
Cog-Net	Proactive	Single	Yes	Shortest path based	NA	Considers traffic load of the route	Lack of sharing spectrum decision information among CUs
C-DSDV	Proactive	Double	Yes	Frequent channel Switching based	Yes	Frequent channel Switch metric improves the system performance	Additional overhead required
DORP	Reactive	Single	No	Delay based	Yes	Suitable for delay sensitive application	Does not include PUs Avoidance
MSCRP	Reactive	Single	No	Shortest path based	Yes	Solves the deafness problem	Adds nodes networking tasks
CAODV	Reactive	NA	No	Shortest path based	NA	Counteract frequency varying PU activities	Does not counteract both frequency and space varying PU activity
STOD-RP	Hybrid	Single	No	Link stability Based	NA	Efficient spectrum-adaptive route recovery method	Lack of analysis of gateway nodes activity (e.g. energy consumption)
Probabilistic Routing	Hybrid	Multi	Yes	Probabilistic routing based	NA	Ensures route stability and availability	Does not consider the spectrum-availability time during the routing decision
Local Coordination Based Routing	Coordination Based Routing	Single	Yes	Delay based	NA	Provides load balancing	Adds control packet Exchanges
Gymkhana	Connectivity Based Routing	Single	No	Link stability based	NA	Balances the traffic load among the different CUs	Lack of sahring spectrum decision information among CUs
SEARCH	Geographic Based Routing	Single	Yes	Delay based	NA	PU avoidance route	CU requires 1 hop neighbors detail information
CRP	PU-Receiver Aware Routing	Single	Yes	Multiple metrics	NA	Explicit protection for PU receivers	Required additional PUs and CUs information
ROSA	Spectrum utility based routing	Double	Yes	Throughput based	Yes	Maximizing the network throughput	Un-assessed data channel

Table 2.1: Summary of the routing protocols in CRAHNs.

Chapter 3

Joint Path and Spectrum Diversity in Routing

The uncertain availability of the spectral resource imposes unique challenges in Cognitive Radio Networks (CRNs). One of the critical issues is to counteract the performance degradation experienced by Cognitive Users (CUs) due to the activity of Primary Users (PUs). Since the activity of primary users varies both in frequency and space domain, diversity techniques can represent an efficient way to address this issue. In this chapter, it is proposed to jointly exploit path and spectrum diversity for efficient use of spectrum in cognitive radio ad-hoc networks (CRAHNs). By jointly exploiting both the diversities, CUs can switch dynamically to different paths and spectrum bands for communicating with each other in presence of frequency- and space-varying primary user activity. This idea is adopted in a routing protocol, referred to as *Dual Diversity Cognitive Ad-hoc Routing Protocol*, and simulation results reveal the effectiveness of introducing joint path and spectrum diversity in routing for CRAHNs.

3.1 Introduction

Cognitive radio (CR) paradigm proposes to enhance the spectrum efficiency by allowing CUs to utilize dynamically and opportunistically the spectrum assigned to the PUs when it is temporarily not used. To reach this aim, CUs must be able to change their transmission and reception parameters to communicate with each other without causing interference to the PUs.

The uncertain availability of the spectral resource imposes unique challenges in CRNs. Specifically, in CRAHNs, the distributed multi-hop architecture, the dynamic network topology and the spectrum availability varying in time and space are some of the key distinguishing factors [5]. Due to these factors, one of the critical issues in CRAHNs is to counteract the performance degradation experienced by CUs because of the activity of PUs. Since such an activity varies both in frequency and space domain, incorporating diversity techniques in routing can provide an effective solution to address this issue.

Most of routing protocols recently proposed for CRAHNs do not exploit diversity techniques [74, 75, 39]. In [74], a protocol for CRAHNs based on the geographic forwarding paradigm has been proposed. The main idea of the protocol is to discover several paths, which are combined at the destination to form the path with the minimum hop count, and it is able to deal with reasonable levels of PU activity changing rate. However, it assumes that most of the nodes be GPS equipped and, most importantly, a mechanism for disseminating the destination location both at the source and at each intermediate node is required. In [75] the authors propose a reactive routing protocol that aims to minimize the interference caused by the CUs to the PUs communications. The proposed protocol exploits the availability of knowledge about both the CUs and the PUs positions for route maintenance. Unlike these works, our protocol do not require any location knowledge for both route discovery and route maintenance. In [39], the authors propose to build a spectrum-tree structure for each channel, storing so all the information about the tree topology and the spectrum availability at the tree-root nodes. As a consequence, the frequency of the spectrum availability changes deeply affects the performance of the proposed protocol. Moreover, the work assumes static or very slowly moving CUs. On the other hand, our work assumes both mobile CUs and dynamic spectrum availability.

However, few proposals have resorted to path- or spectrum-diversity techniques (we refer the reader to [61] for further details). In [90], a path-diversity routing protocol operating only on infrastructure-based network has been proposed. The protocol exploit path-diversity by utilizing multi-path routes. Another path-diversity based routing protocol is proposed in [91] for underlay CRNs. In this work, the authors assume a specific distribution of PUs and CUs in the network, which is not reasonable in CRAHNs. In [71], a source-based routing protocol with path diversity has been proposed for CRNs, and its application in CRAHNs is not reasonable due to high packet header overhead. In [83], a protocol, referred to as cognitive ad-hoc on-demand distance vector (CAODV), has been presented. In this work, the authors have exploited individually path-and spectrum-diversity. Since they have not jointly considered path and spectrum diversity, the effects of PU activity can still degrade the performance of the networks, as shown in Section 3.3. The paper in [92] is the first work that studied joint routing and spectrum allocation problem in multi-hop CRNs. In this work, the authors achieve a solution for that problem by using global knowledge about the network topology, which is not reasonable in CRAHNs.

In this chapter we propose to jointly exploit path and spectrum diversity to counteract the PU activity by exploiting onely local knowledge about network topology, i.e., by exploiting next hop routing. To this aim, the route discovery process complexity increases so that an additional overhead has to be taken into account. Such an overhead, as whose amount is evaluated by simulation experiments in Section 3.5, is well paid if the scenario is heavily dynamic in terms of CU mobility and/or PU activity.

It is worthwhile to underline that the proposal assumes that the available channels (namely the licensed spectrum free from the PU activity) can be used by each CU at the same time [74]. This assumption is reasonable if the CUs are equipped with multiple wireless interfaces. However, also in presence of a single wireless interface, the assumption holds if the presence of an underlying channel coordination mechanism is considered [84, 85].

The rest of the chapter is organized as follows. Section 3.2 describes the network model while Section 3.3 presents the motivation of the proposed work. Section 3.4 discusses the main features of the proposed routing protocol, referred to as Dual Diversity Cognitive Ad-hoc Routing Protocol. Finally, Section 3.5 provides the performance evaluation of the protocol.

3.2 Network model

We assume that the network is composed by CUs that freely move in a two-dimensional cartesian scenario. The PUs, whose positions are assumed to be fixed, operate according to a two-stage on/off switching cycle [74]. The number, the locations and the transmission standards of the PUs are assumed unknown to the CUs, and the primary transmissions are sensed by a spectrum sensing mechanism available at each node. Although such a sensing mechanism is out of the scope of this work, in this work we assume that it is imperfect, i.e. we assume that some strategies are needed at the network layer to assure the minimal interference to PU communications in presence of undetected PU activity.

The CUs communicate only through the licensed portion of the spectrum (i.e. there is no dedicated spectrum for CU control messages), constituted by l channels, each having the same bandwidth. If a primary user is active and its transmission frequency overlaps a CU channel, say channel i, this channel is affected by PU activity in the circular region centered at the PU location with radius equals to the PU interference range. Moreover, to take into account the co-channel interference effects, we assume that the adjacent channels $i-2$, $i-1$, $i+1$, $i+2$ are affected by the PU activity in regions with a radius that decreases with the separation of the channels from channel i [74].

3.3 Motivation

The aim of this section is twofold: *i) to describe the effects of PU activity on routing when it varies in frequency and/or space domain*; *ii) to show the benefits of jointly exploiting path- and spectrum-diversity in CRAHNs*. At this end, a simple scenario is considered in Fig. 3.1, where $\mathrm{CU_A}$ and $\mathrm{CU_D}$ are a CU source and a CU destination node, respectively.

3.3.1 Path Diversity

Path diversity allows CUs to switch dynamically among different paths for communicating with each other in presence of space-domain-dependent PU activity.

Fig. 3.1 (a) shows how the PU activity can affect a routing process whenever it varies in space domain. Here, $\mathrm{CU_B}$ and $\mathrm{CU_C}$ are under the transmission range of two different PUs. By exploiting the path diversity, $\mathrm{CU_A}$ can reach $\mathrm{CU_D}$ through the *optimal path*[1] $\mathrm{CU_A} \rightarrow \mathrm{CU_B} \rightarrow \mathrm{CU_D}$

[1] Optimal according to the adopted metric, i.e., minimum hop count or minimum

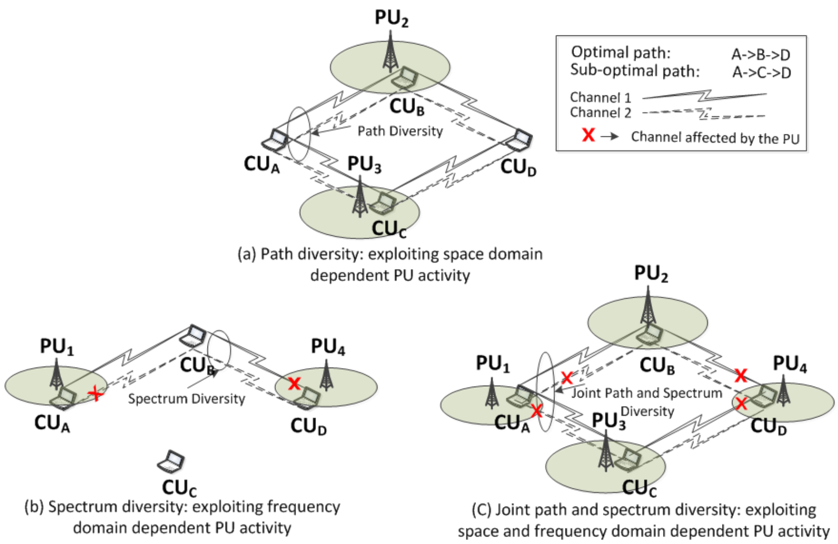


Figure 3.1: Motivation of the proposed work.

(when $\mathrm{PU_2}$ is not active); or the sub-optimal path $\mathrm{CU_A}\rightarrow\mathrm{CU_C}\rightarrow\mathrm{CU_D}$ (when $\mathrm{PU_2}$ is active but $\mathrm{PU_3}$ is not), without the need of a new route discovery process.

However, by only exploiting path diversity, $\mathrm{CU_A}$ can not reach $\mathrm{CU_D}$ when the effect of PU activity varies in frequency domain, as it is depicted in Fig. 1(b). In this example, $\mathrm{CU_A}$ must be able to establish paths through different spectrum bands to communicate with $\mathrm{CU_D}$. Clearly, this requires to exploit spectrum diversity, as it will be described in Section 3.3.2. Therefore, such an example shows that the performance degradation due to the activity of PUs can not be counteracted by the only exploitation of path diversity.

3.3.2 Spectrum Diversity

Spectrum diversity allows CUs to switch dynamically among different channels for communicating with each other in presence of frequency-domain-dependent PU activity.

Fig. 3.1 (b) shows how the PU activity can affect a routing process whenever it varies in frequency domain. Here, $\mathrm{CU_A}$ and $\mathrm{CU_D}$ are par-

Expected Transmission Count (ETX) [98].

tially affected by two different PUs on channel 2 and channel 1, respectively. By exploiting the spectrum diversity, CU_A can still communicate with CU_D through the optimal path composed by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) without interfering the PUs.

However, the performance degradation due to the activity of a PU, which fully affects a path (as shown in Section 3.3.1), can not be counteracted by the only exploitation of spectrum diversity.

3.3.3 Joint Path and Spectrum Diversity

As discuss in the previous subsections, path diversity cannot counteract PU activity that varies in frequency domain, whereas spectrum diversity cannot counteract PU activity that varies in space domain. Differently, joint path and spectrum diversity can provide a promising solution that can solve both the above mentioned limitations.

In fact, joint path and spectrum diversity allows CUs to switch dynamically among different paths and channels for communicating with each other in presence of frequency- and space-domain-dependent PU activity.

Fig. 3.1 (c) shows how the PU activity can affect a routing process whenever it varies in both space and frequency domain. Here, we assume that CU_A, CU_B, CU_C and CU_D are under the transmission range of four different PUs. More in detail, CU_A and CU_D are partially affected by PUs on channel 2 and channel 1, respectively, and CU_B and CU_C are fully affected by PU_2 and PU_3, respectively. Due to the benefit of jointly exploiting path and spectrum diversity, CU_A can communicate with CU_D through the optimal path composed by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) when PU_2 is not active; or the sub-optimal path composed by link $CU_A \rightarrow CU_C$ (on channel 1) and $CU_C \rightarrow CU_D$ (on channel 2) when PU_2 is active but PU_3 is inactive.

Thanks to both the path and spectrum diversity, CU_A can now reach CU_D counteracting the effect of PU activity.

3.4 Dual Diversity Cognitive Ad-hoc Routing Protocol

Dual Diversity Cognitive Ad-hoc Routing Protocol (D^2CARP) is a routing protocol designed for CRAHNs, which exploits the local observations of PU activity. The main feature of D^2CARP is to jointly exploit the path and spectrum diversity in routing. This feature allows CUs to switch dynamically among different paths and channels accounting for the local route decisions during the data forwarding time. As a consequence, D^2CARP is able to adapt to dynamic scenarios caused by PU activity.

The route discovery process of D^2CARP starts with a Route REQuest (RREQ) packet broadcasted by the source to neighbors on each channel not affected by a PU activity, and it ends with one or several routes set up after the reception of Route REPlies (RREPs) from the destination. At the end of the route discovery procedure, the source can take advantage of joint path and spectrum diversity by means of multi-path and multi-channel routes. In a situation, where a PU decides to utilize a channel which is occupied by a CU, in that case, CU vacates the channel immediately and looks for another available channel for continuing the communication with its neighbor. If there is no free channel for its neighbor then CU recalls the route discovery process. The processes of RREQ and RREP phases are described in the following.

3.4.1 Route Request Phase

In RREQ phase, we consider an arbitrary node, say X, receiving a RREQ packet from node Y through an idle channel (namely that is free from PU activity), say channel i. The flow chart of RREQ phase is shown in Fig. 3.2. Here, we mainly discuss how D^2CARP exploits joint path and spectrum diversity in RREQ phase, as described in Algorithm 1.

D^2CARP exploits spectrum diversity by establishing multi-channel reverse routes in RREQ phase, as it is shown from line 4 to line 12 in Algorithm 1. When node X receives the first RREQ, then it creates a reverse path toward the sender node Y through the channel i and it broadcasts a copy of the RREQ packet through each idle channel. If node X receives a further RREQ from the same neighbor Y, but on a different channel, then it creates a reverse route only through that channel. In such a way, node X is able to create reverse routes through the multiple idle channels. Moreover, if node X receives a new or better[2] RREQ, then it updates the reverse route through the channel i.

D^2CARP exploits path diversity by establishing multi-path reverse

[2] Better RREQ according to the adopted metric (i.e., hop count).

Algorithm 1 Path and Spectrum Diversity in RREQ

```
    // node X receives RREQ from node Y through channel i.
 2: if channel i is free from PU then
      // D^2CARP exploits spectrum diversity by establishing multi-channel reverse
      routes in RREQ phase (line 4 to 12).
 4:   if it is the first RREQ for X then
        create a reverse route through the channel i and broadcast RREQ through
        the channels free from PU;
 6:   else if it is additional RREQ from Y but on different channel then
        create a reverse route through that channel;
 8:   else
        if it is the new or better RREQ then
10:       update a reverse route through the channel i;
        end if
12:   end if
      // D^2CARP exploits path diversity by establishing multi-path reverse routes
      in RREQ phase (line 14 to 20).
14:   if X receives RREQ from multiple paths then
        if X == destination node and FHN of RREQ packet != stored FHN in RT
        and Y != NHN in RT and hop_rreq ≤ min_hop then
16:       create a reverse route through the channel i;
        else
18:       X discards the RREQ;
        end if
20:   end if
      if X has valid route for destination then
22:     send RREP to Y;
      else
24:     X discards the RREQ;
      end if
26: else
      X discards the RREQ;
28: end if
```

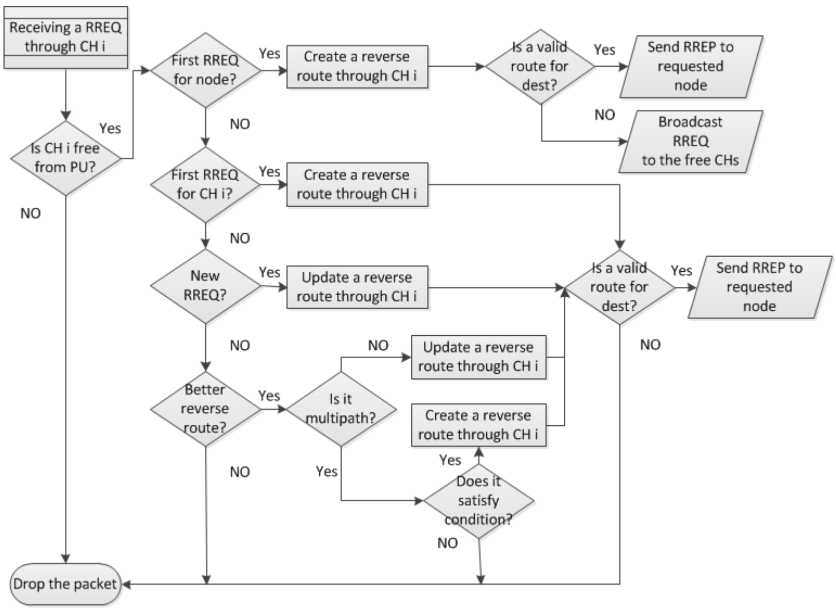


Figure 3.2: The flow chart of RREQ phase.

routes in RREQ phase, as it is shown from line 14 to line 20 in Algorithm 1. D^{2}CARP singles out the paths according to the First Hop Node (FHN), which is a field of RREQ packet. When a node receives a RREQ directly from a source then the receiving node's ID will be stored in the FHN. If the FHN inside the RREQ packet is different to the stored FHN in the Routing Table (RT), then this RREQ is received from a different path. In that case, if the multi-path conditions are satisfied, then the node creates a reverse route through channel i, otherwise it drops the packet. The multi-path conditions to be assured are: i) the receiving node must be the destination; ii) the candidate path must not share any intermediate node with previous established paths (i.e., when FHN of RREQ is not already present in other FHN of RT and node Y is not a Next Hop Node (NHN) in RT); iii) the value of the hop count field in RREQ packet (hop_{rreq}) must be less or equal than minimum hop (min_{hop}) for the particular source. The first condition implies that the multi-path discovery procedure is confined to the final destination in order to limit the overhead. The second condition introduces a robust behavior when a node is not any more available due to the PU appearance. The third condition easily assures the shortest (in terms of hops) paths. Finally, if node X has a valid route for the destination, then it sends RREP to node Y, otherwise drops the RREQ packet.

3.4.2 Route Reply Phase

In RREP phase, we consider an arbitrary node, say P, receiving a RREP packet from node Q through an idle channel, say channel i.The flow chart of RREP phase is shown in Fig. 3.3. Here, we mainly discuss how D^{2}CARP exploits joint path and spectrum diversity in RREP phase, as described in Algorithm 2.

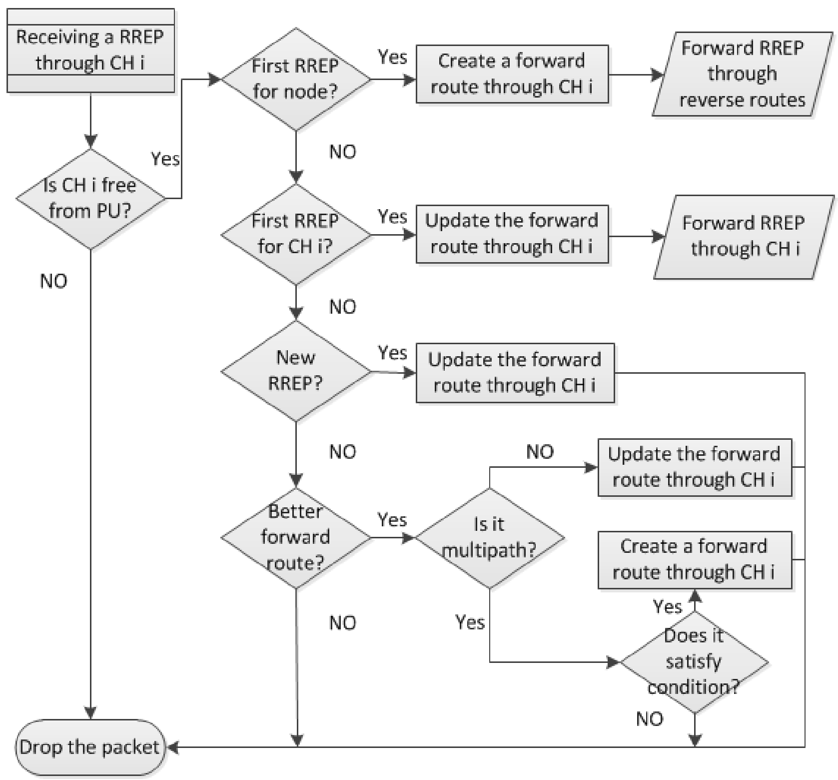


Figure 3.3: The flow chart of RREP phase.

D^{2}CARP exploits spectrum diversity by establishing multi-channel forward routes in RREP phase, as it is shown from line 4 to 12 in Algorithm 2. When node P receives the first RREP packet, then it creates a forward route through channel i and forwards RREP to all channels that have reverse route. If node P receives a further RREP from the same neighbor Q, but on a different channel, then it creates a forward route and forwards RREP only through that channel. In such a way, node P is able to create forward routes through the multiple idle channels.

D^{2}CARP exploits path diversity by establishing multi-path forward routes in RREP phase, as it is shown from line 14 to 18 in Algorithm 2. Like in RREQ phase, D^{2}CARP singles out the paths according to the FHN of RREP packet. When a node receives a RREP directly from a destination, then the receiving node's ID will be stored in the FHN. If the FHN inside the RREP packet is different to the stored FHN in the RT, then this RREP is received from a different path. In that case, if the multi-path conditions are satisfied, then the node creates a forward route through the same channel. The multi-path conditions to be assured are: i) the receiving node must be the source; ii) the candidate path must not share any intermediate node with previous established paths (i.e., when FHN of RREP is not already present in other FHN of RT and node Q is not a Next Hop Node (NHN) in RT); iii) the value of the hop count field in RREP packet (hop_{rrep}) must be less or equal than minimum hop (min_{hop}) for the particular destination. Finally, node P drops the RREP packet.

3.4.3 Route Maintenance

Topology changes due to node mobility or wireless propagation instability are handled with traditional Route ERRor (RERR) packets, while the route maintenance due to changes in spectrum availability exploits an additional types of packets, namely, the Primary User Route ERRor (PU-RERR) packets, as shown in Fig. 3.4. The main difference between the two type of packets is the scope. The RERRs generally have a wide scope, since they are used to advice all the intermediate nodes belonging to a route that a link is failed and a new route discovery session is needed. On the other hand, the PU-RERRs have a local scope, since they are used to inform the neighbors that some PU activity has been sensed on a certain channel and, therefore, it is necessary to use a different channel for packet forwarding.

More in detail, when some PU activity is detected by a CU on a certain channel, say channel i, the CU invalidates all the routing entries through such a channel and it informs the CU neighbors that the channel is now unavailable with a PU-RERR packet. The CUs that receive the

Algorithm 2 Path and Spectrum Diversity in RREP

```
    // node P receives RREP from node Q through channel i.
 2: if channel i is free from PU then
      // D²CARP exploits spectrum diversity by establishing multi-channel forward
      routes RREP phase (line 4 → line 12).
 4:   if it is the first RREP for P then
        create a forward route through the channel i and forward RREP to all
        channels that exists a reverse route;
 6:   else if it is additional RREP from Q but on different channel then
        create a forward route and forward RREP through that channel;
 8:   else
        if it is the new or better RREP then
10:       update a forward route through the channel i;
        end if
12:   end if
      // D²CARP exploits path diversity by establishing multi-path forward routes
      in RREP phase (line 14 to 18).
14:   if P receives RREP from multiple paths then
        if P == source node and FHN of RREP packet != stored FHN in RT and
        Q != NHN in RT and hop_rrep ≤ min_hop then
16:       create a forward route through the channel i;
        end if
18:   end if
    end if
20: P discards the RREP;
```

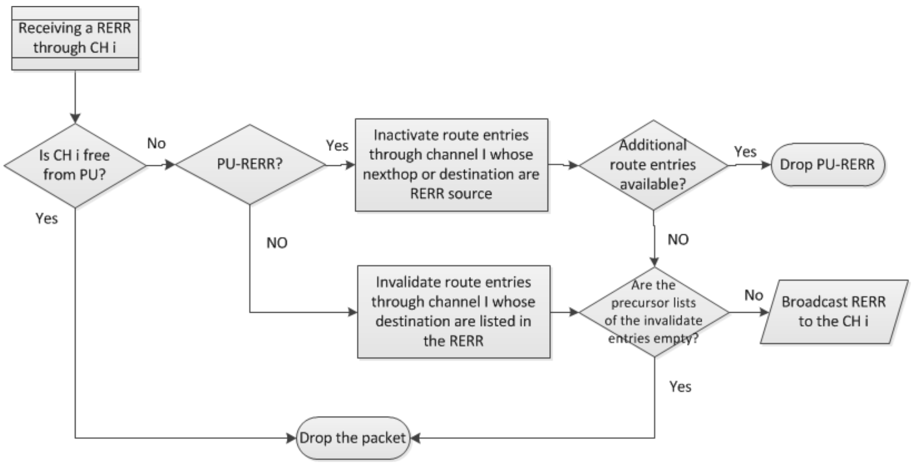


Figure 3.4: The flow chart of RERR phase.

PU-RERR invalidates the routes through channel i that involves the PU-RERR source. In such a way, the routing protocol is able to minimize the interference to PU communications in case of imperfect spectrum sensing.

We note that the PU-RERR packets allows D^2CARP to handle dynamic spectrum availability without introducing excessive overhead. In fact, when a CU receives a PU-RERR, it checks if additional routes are available in its routing table. If so, the CU can forward the traffic through the additional route(s), otherwise, a new route discovery session is started by using a traditional RERR packet.

When CU is released from PU, i.e., PU is switched from *"on"* state to *"off"* state, it broadcasts a packet named *req-enable-channel* towards its neighbors. After receiving this packet, the neighbors update their routing table and send a packet named *rep-enable-channel* towards the sender of the *req-enable-channel* packet. Finally, the CU (which is released from PU) will update its routing table according to the *rep-enable-channel* packets received from the neighbors and it will drop the packets.

3.4.4 Packet Forwarding

To exploit the path and spectrum diversity, source CU first singles out multiple paths according to path metric among the discovered paths. Then, the data flow is randomly partitioned on the available paths.

In such a way, D^2CARP exploits path diversity. For exploiting spectrum diversity, CU can switch different channels while PU arrives in the present one.

3.5 Performance Evaluation

In this section, a performance comparison of D^{2}CARP with CAODV [83] is carried out by numerical simulation experiments to assess the benefits of joint path and spectrum diversity. Since CAODV is designed for CRAHNs by exploiting path or spectrum diversity, it is considered as a reference protocol. Here we consider the spectrum diversity version of CAODV, since it outperforms the path diversity version. We have carried out the performance comparison by using the Network Simulator 2 (ns-2) [86]. Ns-2 has been extended to multi-radio multi-channel environments according to [87].

3.5.1 Simulation Setup

CUs move according to the random *way point* model in a square area, whose size has been set such as it fits with a node density equal to 400 $nodes/Km^2$. The transmission range of the CUs has been set to 120 m, the transmission standard is the IEEE 802.11b and the propagation model is the *Two-Ray Ground* one. The transmission range of the PUs, whose positions are assumed static, has been set to 300 m and their activity is modeled according to a two- stage *on/off* process with exponential distribution with rate parameter λ. In the following we refer to $\frac{1}{\lambda}$ as the PU activity time.

The workload is modeled as Constant Bit Rate (CBR) data packets 1000 bytes along over User Datagram Protocol (UDP) connections, and each node generates one data flow toward a destination selected randomly. Accounting for the Gupta-Kumar [88] bound, the throughput generated by each source has been set to $\frac{W}{10\sqrt{n}}$, where W is the link data throughput and n is the number of CUs in the network.

The duration of each run is 1060 s and the data traffic is active in the interval [60,1000] seconds. For each experiment, we performed five runs computing both the average value and the standard deviation for each metric: (i) Packet Delivery Ratio (PDR); (ii) hop count; (iii) end-to-end delay; (iv) routing overhead. The summary of the simulation parameters is shown in Table 3.1.

3.5.2 Numerical Results

In Fig. 3.5 - 3.10, it is shown the performance comparison between D^{2}CARP and CAODV versus the PUs or CUs. We use four different metrics to compare the performance of the considered protocols, namely, Packet Delivery Ratio (PDR), overhead, delay, and hop count.

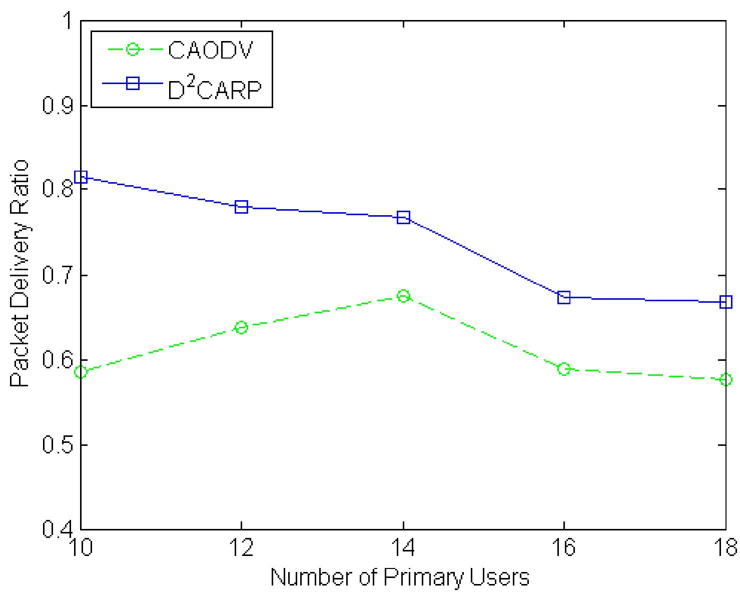


Figure 3.5: Performance behavior of D^2CARP and CAODV in terms of PDR versus the number of PU.

In Fig. 3.5, the performance behavior of D^{2}CARP and CAODV in terms of PDR versus the number of PUs is analyzed in relatively large network (160 CUs). We observe that the D^{2}CARP exhibits a significant improvement compared to CAODV when the PUs number is low, while it performs better or comparable to CAODV when the PUs number is higher. This behavior can be justified because the load of a crowded network is distributed by using multi-path routes in D^{2}CARP. Therefore, a less path congestion will occur.

In Fig. 3.6, the performance behavior of both the protocols versus the number of PUs is analyzed in terms of overhead. Since we consider

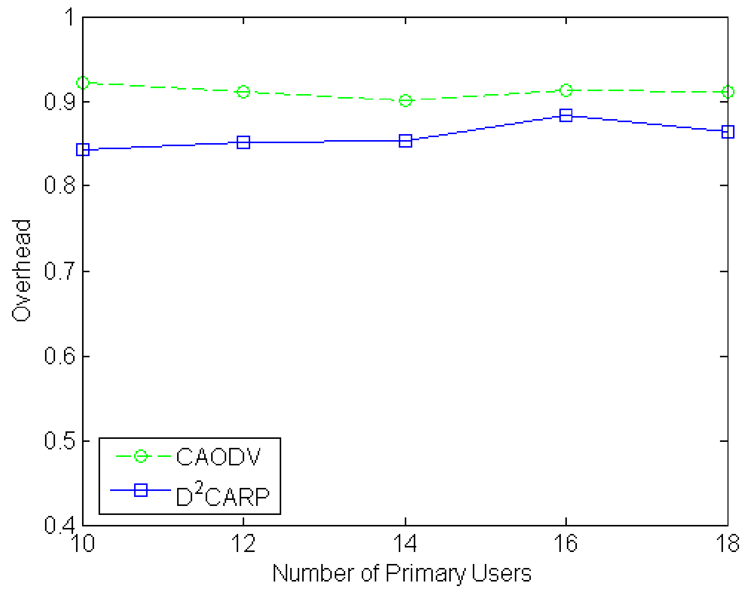


Figure 3.6: Performance behavior of D^2CARP and CAODV in terms of Overhead versus the number of PUs.

a relatively large network (160 CUs), in both the cases the overhead is high (around 90%). However, we note that the overhead of D^{2}CARP is lower than CAODV for both low and high number of PUs. This behavior can be explained by considering how D^{2}CARP handles the PU arrival on a certain channel and a path. Due to the dynamic use of different paths and channels, the probability that a new path must be established during data sending time is lower, reducing so the overhead of D^{2}CARP with respect to CAODV.

In Fig. 3.7, the performance behavior of both protocols is analyzed in terms of delay-time with the number of PUs. We observe that for both the protocols when the PU number is low, the delay is low as well, while for higher values the delay increases. However, the D^{2}CARP outperforms CAODV in both low and high number of PUs. Due to the robustness of the path, assured by the second multi-path condition (see Section 3.4.1 and Section 3.4.2), less interruption occurs during the communication, reducing so delay-time of D^{2}CARP.

In Fig. 3.8, the performance behavior of both the protocols is ana-

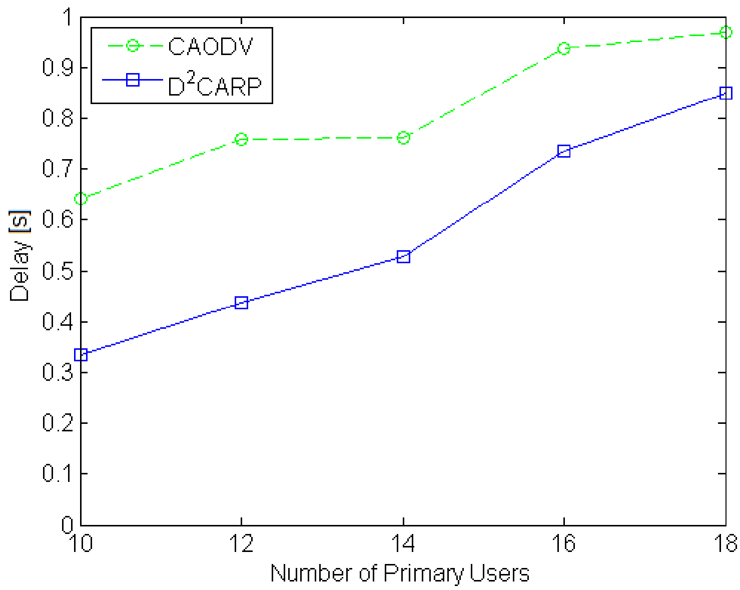


Figure 3.7: Performance behavior of D^2CARP and CAODV in terms of Delay versus the number of PU.

lyzed in terms of hop count when the number of PUs increases. We observe a similar behavior of both the protocols with low and high number of PUs. This behavior is reasonable because, during the route discovery process, both the protocol choose the path in according to the minimum number of hop.

In Fig. 3.9, the performance behavior of both the protocols is evaluated in terms of overhead when the number of CUs increases. We observe that D^2CARP exhibits an improvement compared to CAODV for both low and high number of CUs. This behavior can be justified according to the same reasoning related to Fig. 3.6.

In Fig. 3.10, the performance behavior of both the protocols is analyzed in terms of delay-time when the number of CUs increases. We observe that D^2CARP performs better or comparable to CAODV when the CU number is lower but it significantly outperforms CAODV when the CU number is high. This behavior can be justified according to the same reasoning regarding Fig. 3.7.

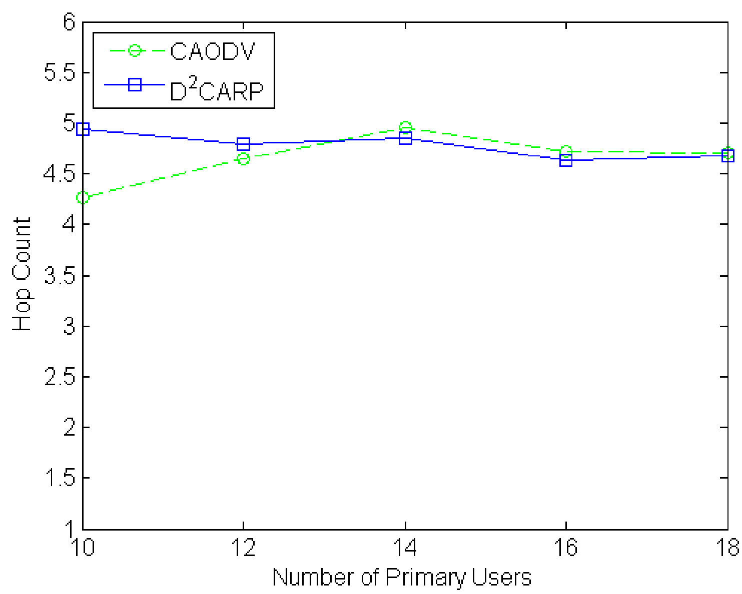


Figure 3.8: Performance behavior of D^2CARP and CAODV in terms of Hop Count versus the number of PU.

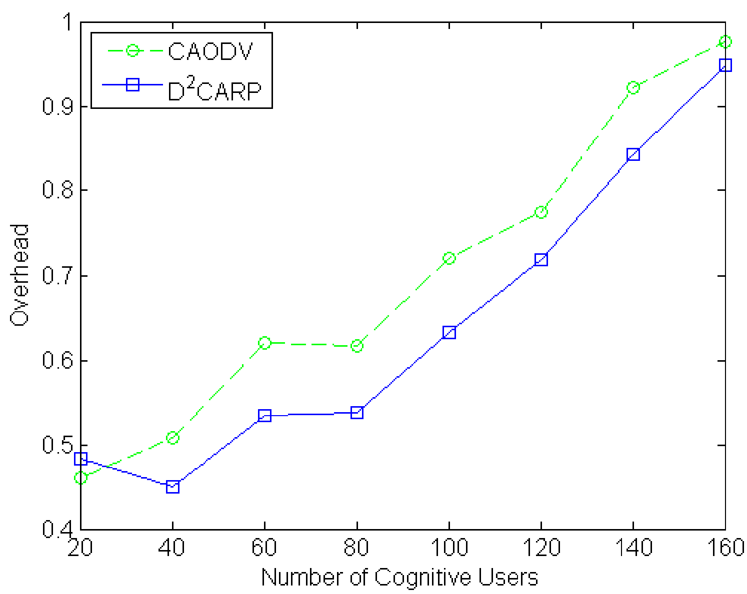


Figure 3.9: Performance behavior of D^2CARP and CAODV in terms of Overhead versus the number of CUs.

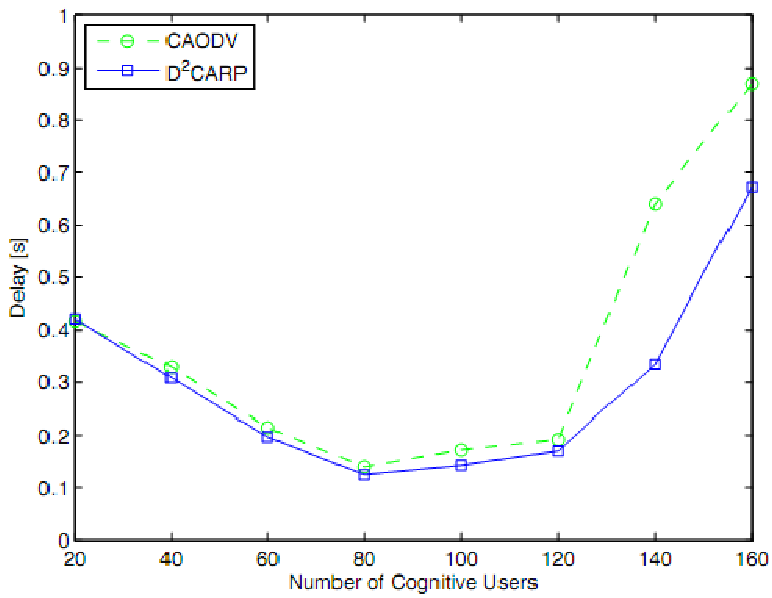


Figure 3.10: Performance behavior of D^2CARP and CAODV in terms of Delay versus the number of CUs.

Simulation Parameters	
CU number	160
CU transmission range	120 m
CU node density	400 nodes/Km^2
CU speed	2 m/s
Mobility model	Random Way-Point model
Data Traffic model	Constant Bit Rate (CBR) over UDP
Propagation model	Two-Ray Ground model
PU number	[10,12 . . , 18]
PU Tx range for the overlapped channel i	300 m
PU Tx range for adjacent channels *(i - 1, i + 1)*	150 m
PU Tx range for adjacent channels *(i - 2, i + 2)*	75 m
PU activity parameter	200
Duration of Simulation	1060 seconds
Active data traffic interval	[60-1000]

Table 3.1: Simulation Parameters of the experiments.

Chapter 4

MCAST: Mobility-aware Channel-Availability based channel Selection Technique

A key issue in Cognitive Radio Networks (CRNs) is the design of a channel selection technique that guarantees to utilize the highest available channel in presence of the dynamic activity of Primary Users (PUs). Usually, the channel selection techniques that operate in this kind of network are based on the channel-availability probability. In the static PU scenario, this probability can be *a priori* known or simply estimated from the channel occupancy history. However, in the mobile PU scenario, this probability dynamically varies in time due to the changes of the PU position. In order to exploit the dynamic variation of the channel availability, in this work we design a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) that maximizes the network performance by selecting the channel with the highest channel availability probability in a given temporal interval. The simulation results highlight the benefits of the proposed technique in presence of PU mobility. Moreover, we evaluate the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric designed for CRNs.

4.1 Introduction

In Cognitive Radio Networks (CRNs), the channel selection techniques are usually based on the knowledge of the Channel-Availability Probability (CAP), i.e., the probability that the channel is available for the Cognitive Users (CUs) without causing interference against the PUs. In fact, this knowledge enables the CU to select the channel with the highest availability and, consequently, it improves the network performance and satisfies the quality-of-service (QoS) requirements [75]. Usually, the CAP coincides with the probability that at a certain time the PU is inactive, and can be *a priori* known or simply estimated from the channel occupancy history [75]. However, this assumption is valid when the PU is static, i.e., the CU is always inside the transmission range of the PU.

On the other hand, in the mobile PU scenario, the CAP dynamically varies in time due to the changes of the PU position. For instance, if at a certain time the CU is outside the *protection range*[1] of an arbitrary PU, then the CAP is independent from whether the PU is inactive or not. Due to the PU mobility, after a certain interval of time, the CU might be inside the protection range of the PU, then the CAP depends on the probability that the PU is inactive. Since the best performance is guaranteed by the channel with the highest CAP assumed at a given time, a fundamental key issue in CRNs is the *design of a channel selection technique that maximizes the network performance by exploiting the dynamic variation of the channel availability caused by the PU mobility.*

Basically, most of the works in literature consider the static PU scenario where the CAP does not vary in time. In [105], the authors propose an opportunistic Multi-Channel MAC with QoS provisioning for distributed CRNs, where CUs use the previous channel scanning results to select those channels with the highest channel-availability estimate. In [106], the authors propose an opportunistic periodic MAC protocol where the CUs cooperate each other to share the channel-availability information. In [75], the authors propose a routing metric that aims to minimize the interference caused by the CUs against the static PUs. In [102], the authors propose an optimal routing metric for CRNs where the channel is selected based on channel occupancy history.

[1] It is defined as the maximum distance between the PU and the CU at which the CU transmission does not interfere the PU communication on an arbitrary channel. It is determined by the PU transmission range and by the CU interference range.

However, the design of a channel selection technique that accounts for the CAP in presence of PU mobility has not yet been addressed in literature. For this reason, we design a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) that maximizes the network performance by selecting the channel with the highest CAP in a given temporal period. To the best of our knowledge, this is the first time this issue is addressed.

Specifically, the contribution of this work can be summarized as follows. First, we derive the channel-availability estimation method in presence of PU mobility. Then, we prove that the proposed channel selection technique takes advantage from the dynamic variation of channel-availability caused by the PU mobility and, consequently, outperforms the typical method which is only based on the PU temporal activity. The simulation results highlight the benefits of the proposed technique. Moreover, we evaluate the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric, referred to as Optimal Primary-aware routEquAlity (OPERA) [102], designed for CRNs.

The rest of the chapter is organized as follows. In Section. 4.2 we introduce the problem statement. In Section 4.3 we discuss about the network model, while in Section 4.4 we describe the channel-availability estimation process. We describe the proposed MCAST in Section 4.5. Finally, the performances are evaluated through simulations in Section 4.6.

4.2 Problem Statement

In this section, first we describe the channel-availability estimation method in the static PU scenario, then we formulate the problem in the mobile PU scenario. Finally, we present our proposal.

4.2.1 Static PU Scenario

In the static PU scenario, the geographic location of each PU is fixed, and the CU is always inside the PU transmission range, as shown in Fig. 4.1. The CAP of an arbitrary channel m, defined as the probability that at a certain time the channel m is available for the CU communication, coincides with the PU inactive probability, i.e., P_{off}^{m}. This probability can be *a priori* known or simply estimated based on the channel occupancy history [75]:

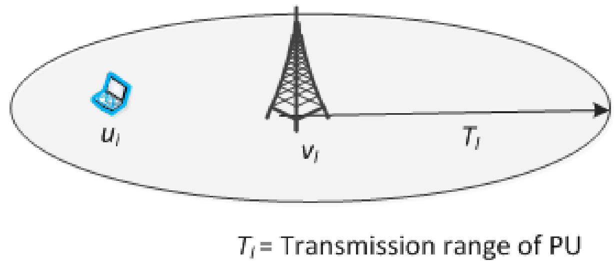


Figure 4.1: CAP in presence of static PU.

$$P^m_{off} = \frac{\alpha^m}{\alpha^m + \beta^m} \tag{4.1}$$

where $\frac{1}{\alpha^m}$ and $\frac{1}{\beta^m}$ are the average *on* and *off* times for the *m-th* channel, respectively. The *on* time refers to the period where the *m-th* channel is sensed to be occupied by the PU, while the *off* time indicates the channel is free for CR transmission.

Based on this information, the CU selects the channel m with the highest PU inactive probability P^m_{off}, referred to as *typical method*.

4.2.2 Mobile PU Scenario

In the mobile PU scenario, the geographic location of each PU is not fixed and the channel availability dynamically varies in time. In Fig. 4.2 (a), the transmission of the *i-th* CU, denoted as u_i, does not affect the PU receiver at time t, since u_i is outside the protection range of the *l-th* PU transmitter, denoted as v_l. However, v_l is moving toward u_i at time t, then after a certain interval of time, in Fig. 4.2 (b), the transmission of u_i might affect the PU receiver at time instant t', since u_i is inside the protection range of v_l. Therefore, the CAP varies in the interval $[t, t']$.

In this scenario, if the CU selects the channel accounting to the *typical method*, it will not achieve the best performance. We discuss this issue with an example. As shown in Fig. 4.3, there are two PUs, denoted as v_l and v_n, which are communicating on channel 1 and 2, respectively. Due to the PU mobility, in a certain interval of time $[t_0, t_0 + \Delta]$, the CAP depends on two factors: *i)* The PU inactive probability, i.e., P^m_{off}; *ii)* The probability that the CU transmission does not affect the PU while it is active. The *typical method* selects the best channel considering only

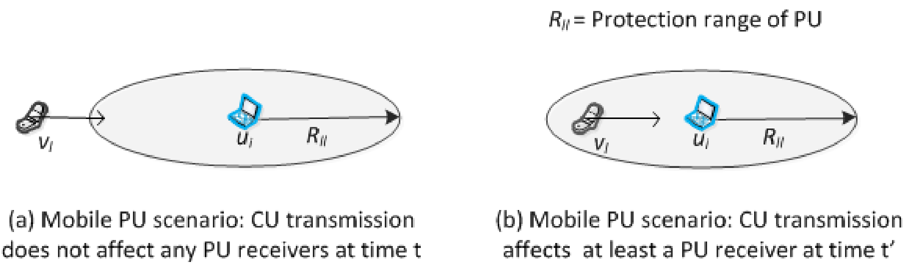


Figure 4.2: CAP in presence of mobile PU.

the first factor. Since $P^{(1)}_{off}$ is greater than $P^{(2)}_{off}$, the best channel in according to the *typical method*[2] is channel 1. However, in presence of PU mobility, the selection of channel 1 does not assume the best choice in terms of channel availability. In fact, as shown in the example reported in footnote[3], according to the procedure which considers both the factors, referred to as *mobility-aware method*, the channel with the highest channel availability is channel 2. As a result, at a certain time t_0, the *mobility-aware method* achieves the best performance in presence of PU mobility by selecting the channel with the highest channel availability for the next interval of time $[t_0, t_0 + \Delta]$.

From the above example, it is evident the need to design a proper channel selection technique that maximizes the network performance by exploiting the dynamic variation of the CAP caused by the PU mobility.

4.2.3 Proposed Method

The proposed channel selection technique is based on the channel-availability estimation method in order to predict the channel-availability for a given interval of time. The method is described as follows. First, a distance estimation procedure is adopted. It is depicted in Fig. 4.4 where the *i-th* CU and the *l-th* PU are denoted as u_i and v_l, respectively, and R_{il} is the *protection range*. The PU v_l is mobile whose position at a

[2] *typical method*: $P^{(1)}_{off} = 0.6$ and $P^{(2)}_{off} = 0.4$.
[3] *mobility-aware method*:
$p^{(1)}_{il} = P^{(1)}_{off} + (1 - P^{(1)}_{off}) P\{CU\ u_i\ does\ not\ interfere\ with\ the\ communication\ of\ PU\ v_l\}$
$= 0.6 + 0.4 \times 0 = 0.6$
$p^{(2)}_{in} = P^{(2)}_{off} + (1 - P^{(2)}_{off}) P\{CU\ u_i\ does\ not\ interfere\ with\ the\ communication\ of\ PU\ v_n\}$
$= 0.4 + 0.6 \times 1 = 1$

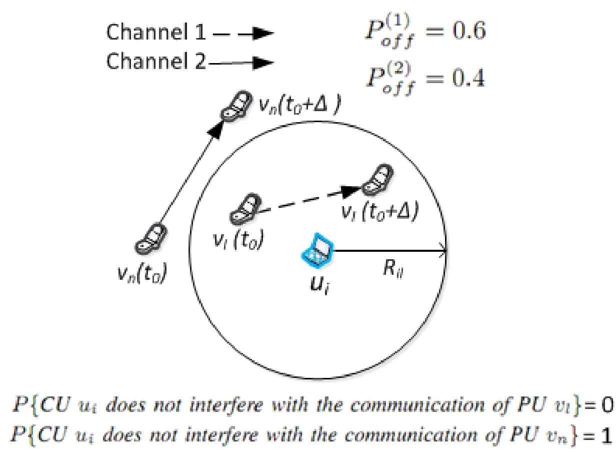


Figure 4.3: Typical method fails in selecting the best channel between 1 and 2 in terms of spectrum availability. It selects channel 1, although channel 2 is the best one.

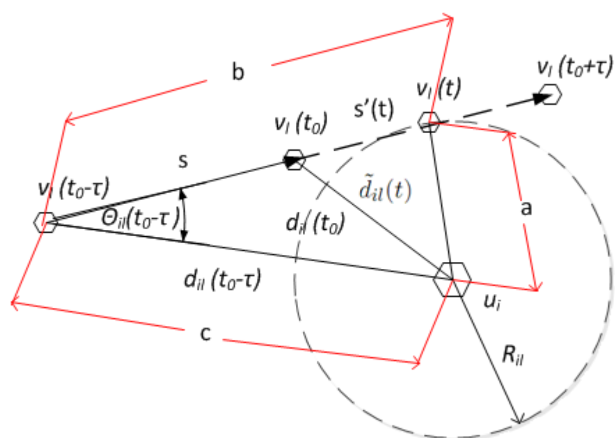


Figure 4.4: Channel-Availability Estimation for PU mobility scenario.

generic time instant t is denoted, for simplicity of notation, as $v_l(t)$, and the distance between u_i and v_l is denoted as $d_{il}(t)$. The PU position is updated every τ sec. During the interval τ, the CU does not know the effective PU position, thus *a distance estimation procedure should be derived to predict the PU positions during this temporal interval.* At the present time t_0, the CU can calculate several parameters related to the previous interval $[t_0 - \tau,\, t_0]$, such as $d_{il}(t_0 - \tau)$ and $d_{il}(t_0)$, the traveled distance of v_l during the interval $[t_0 - \tau,\, t_0]$ denoted as s, the estimated movement direction of v_l toward u_i at time $(t_0 - \tau)$ denoted as $\tilde{\theta}_{i,l}(t_0 - \tau)$. Based on these information, along with the estimated traveled distance of v_l during the interval $[t_0,\, t]$ denoted as $s'(t)$, u_i can estimate the distance $\tilde{d}_{il}(t)$ when t belongs to the next temporal period $[t_0,\, t_0 + \tau]$.

Based on the estimated distance, it is possible to estimate the CAP at a certain instant of time t and consequently to predict the CAP for each channel by averaging it over the next temporal period. Finally, the method selects the best channel namely, the one with the highest average CAP for the next temporal interval.

4.3 Network Model and Preliminaries

In this section, we first describe the network model. Then, we provide several definitions that will be used throughout the work.

4.3.1 Network Model

PU Network Model: The PUs move according to the Random WayPoint Mobility (RWPM) model [109] inside a square network region $\mathcal{A}$. Each PU randomly chooses a destination point in $\mathcal{A}$ according to a uniform distribution, and it moves towards this destination with a velocity modeled as a random variable uniformly distributed in $[v_{min}, v_{max}]$ m/s and, statistically independent of the destination point. During each PU movement period, it is assumed that the PU does not change its direction and velocity. The PU position $v_l(t) = \left(v_l^x(t); v_l^y(t)\right)$ is updated every τ sec by means of cooperative localization techniques or accessing to a database. The PU traffic on the m-th channel is modeled as a two-state birth-death process [108]. Moreover, we consider two different PU spectrum occupancy models [103]. In the first model called Single PU for Channel (SPC), the PUs roaming within the network region using different channels. In the second model called Multiple PUs for Channel (MPC), different mobile PUs can use the same channel.

CU Network Model: The CUs are assumed static[4], where $u_i(t)$ denotes the position of the *i-th* CU that is constant in time. Each CU obtains its location information[5] once during the network initialization, whereas it can update the PU position[6] every τ seconds.

All the symbols used in the work are reported in Table 4.1.

4.3.2 Definitions

Definition 1 (**Protection Range**). *It is the maximum distance between the l-th PU and the i-th CU at which the transmission of the CU does not interfere with the communication of the PU. It is determined by the i-th CU interference range I_i and the l-th PU transmission range T_l:*

$$R_{il} = I_i + T_l \tag{4.2}$$

Remark. *If the CU is using the channel occupied by the PU at time t when their euclidean distance $d_{il}(t) = \|u_i(t) - v_l(t)\| < R_{il}$, then the CU transmission causes interference to PU communication, as shown in Fig. 4.5:*

Definition 2 (**Channel-Availability Probability**). *The channel availability probability $p^m_{il}(t)$ is the probability that at time t the channel m is available for the transmission of the i-th CU without causing interference to the communication of the l-th PU:*

$$p^m_{il}(t) = P^m_{off} + (1 - P^m_{off})1_{R_{il}}(d_{il}(t)) \tag{4.3}$$

where P^m_{off} is the PU inactive probability, and $1_{R_{il}}(d_{il}(t))$ is the indicator function defined as $1_{R_{il}}(d_{il}(t)) = 1$ if $d_{il}(t) > R_{il}$ otherwise it is equal to zero.

[4] It is straightforward to prove that the derived expressions hold also if we assume mobile CR users and static PUs.

[5] The CU can obtain its location either directly through dedicated positioning systems such as Global Positioning System (GPS) or indirectly through location estimation algorithms.

[6] It is reasonable to assume that the CU cannot access the PU location in each time instant t, since the PU location is time-variant and it is obtained through either location estimation algorithms [110, 111, 112] or dedicate databases.

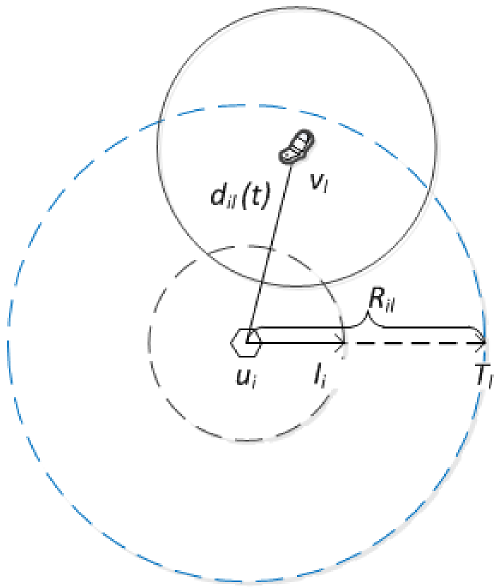


Figure 4.5: Protection Range.

Remark. *From the above definition it follows that the CAP at time t equals to the PU inactive probability when $d_{il}(t) \leq R_{il}$, otherwise it equals to one.*

4.4 Channel-Availability Estimation

As explained in the previous section, since the CU does not know the effective PU position during τ, a distance estimation method should be derived to predict the channel availability during this temporal interval, with the aim to select the channel with the highest CAP. Thus, in this section we single-out the distance estimation procedure and the estimated CAP expression in both Single PU for Channel (SPC) (Section 4.4.1) and Multiple PU for Channel (MPC) (Section 4.4.2) scenarios. Finally, we discuss the trade-off that exists between the updating period τ of the PU position and the distance estimation error (Section 4.4.3).

4.4.1 CAP estimation in SPC scenario

In this subsection, we derive (Theorem 1) the estimation $\tilde{p}_{il}^{m}(t)$ of the CAP when $t \in [t_0, (t_0 + \tau)]$ in SPC scenario under the following assumptions: i) The CU knows the PU position at the actual time instant t_0 and at the previous time instant $t_0 - \tau$; ii) The PU does not change its direction and velocity during the interval $[t_0 - \tau, t_0 + \tau]$. Since the proof of Theorem 1 requires an intermediate result, we first present it in Lemma 1.

Lemma 1. *The estimated distance $\tilde{d}_{il}(t)$ between the i-th CU and the l-th PU at time instant $t \in [t_0, (t_0 + \tau)]$ is given by:*

$$\tilde{d}_{il}(t) = \sqrt{(s + s'(t))^2 + (d_{il}(t_0 - \tau))^2 - 2(s + s'(t))d_{il}(t_0 - \tau)\cos(\tilde{\theta}_{il}(t_0 - \tau))} \quad (4.4)$$

where s and $s'(t)$ are the distances traveled by the l-th PU during the temporal intervals $[t_0 - \tau, t_0]$ and $[t_0, t]$, respectively, and $\tilde{\theta}_{il}(t_0 - \tau)$ is the estimated movement direction of the l-th PU towards the i-th CU at the time instant $(t_0 - \tau)$.

Proof. It is straightforward to prove the lemma by considering the triangle with the sides denoted as a, b and c as shown in Fig. 4.4. It is well known that:

$$a^2 = b^2 + c^2 - 2bc\, cos(\tilde{\theta}_{i,l}(t_0 - \tau)) \quad (4.5)$$

where $a = \tilde{d}_{il}(t)$ is the estimated distance at time t, $b = s + s'(t)$ is defined by means of eq. (4.6) and (4.7), $c = d_{il}(t_0 - \tau)$ is defined in eq. (4.8), and the estimated PU direction $\tilde{\theta}_{il}(t_0 - \tau)$ is defined in eq. (4.9). Thus, we have:

$$s = \|v_l(t_0 - \tau) - v_l(t_0)\| = \sqrt{(v_l^x(t_0 - \tau) - v_l^x(t_0))^2 + (v_l^y(t_0 - \tau) - v_l^y(t_0))^2} \quad (4.6)$$

where $\left(v_l^x(t_0 - \tau); v_l^y(t_0 - \tau)\right)$ and $\left(v_l^x(t_0); v_l^y(t_0)\right)$ are the coordinates, in a Cartesian reference system, of the PU position at time $(t_0 - \tau)$ and t_0, and:

$$s'(t) = \frac{s(t - t_0)}{\tau} \quad (4.7)$$

Then, we have:

$$\begin{aligned} d_{il}(t_0 - \tau) &= \|v_l(t_0 - \tau) - u_i(t_0 - \tau)\| = \\ &= \sqrt{(v_l^x(t_0 - \tau) - u_i^x(t_0 - \tau))^2 + (v_l^y(t_0 - \tau) - u_i^y(t_0 - \tau))^2} \end{aligned} \quad (4.8)$$

where $(u_i^x(t_0-\tau); u_i^y(t_0-\tau))$ denote the coordinates of the CU position which are constant in time. Finally, we have:

$$\tilde{\theta}_{il}(t_0-\tau) = \cos^{-1}\left(\frac{s^2 + d_{il}^2(t_0-\tau) - d_{il}^2(t_0)}{2sd_{ij}(t_0-\tau)}\right) \tag{4.9}$$

with $d_{il}(t_0)$ given by:

$$d_{il}(t_0) = \|v_l(t_0) - u_i(t_0)\| = \sqrt{(v_l^x(t_0) - u_i^x(t_0))^2 + (v_l^y(t_0) - u_i^y(t_0))^2} \tag{4.10}$$

where $\left(v_l^x(t_0); v_l^y(t_0)\right)$ are the coordinates of the PU position at time t_0.

By substituting the values of a, b and c in eq. (4.5) we can prove this lemma. □

By means of Lemma 1, we can now derive the expression of the estimated CAP $\tilde{p}_{il}^m(t)$ when $t \in [t_0, (t_0+\tau)]$ in the SPC scenario.

Theorem 1. *The estimated CAP $\tilde{p}_{il}^m(t)$ at time $t \in [t_0, (t_0+\tau)]$ assume the following expression:*

$$\tilde{p}_{il}^m(t) = \begin{cases} 1 & \textit{if } \tilde{d}_{il}(t) > R_{il} \\ P_{off}^m & \textit{otherwise} \end{cases} \quad \forall\, t \in [t_0, (t_0+\tau)] \tag{4.11}$$

Proof. It follows by accounting for Lemma 1. □

Remark. *The estimated CAP $\tilde{p}_{il}^m(t)$ depends on the estimated distance $\tilde{d}_{il}(t)$. Since it is assumed that the l-th PU does not change the velocity and direction during the interval $[t_0-\tau, t_0+\tau]$, the estimation procedure will encounter an error that depends on the PU mobility parameters and the temporal period τ. The trade-off is discussed in the subsection 4.4.3.*

4.4.2 CAP estimation in MPC scenario

In this subsection, we derive (Theorem 2) the expression of the estimated CAP when $t \in [t_0, (t_0+\tau)]$ in the MPC scenario, under the same assumptions of the Theorem 1.

Theorem 2. *If a number N of PUs, which are the elements of a primary user set V, use the same channel m simultaneously, then the estimated CAP $\tilde{p}_{iV}^m(t)$ at time $t \in [t_0, (t_0+\tau)]$ assume the following expression:*

$$\tilde{p}_{iV}^m(t) = \begin{cases} 1 & \textit{if } \tilde{d}_{il}(t) > R_{il} \quad \forall\, l \in V \\ P_{off}^m & \textit{otherwise} \end{cases} \quad \forall\, t \in [t_0, (t_0+\tau)] \tag{4.12}$$

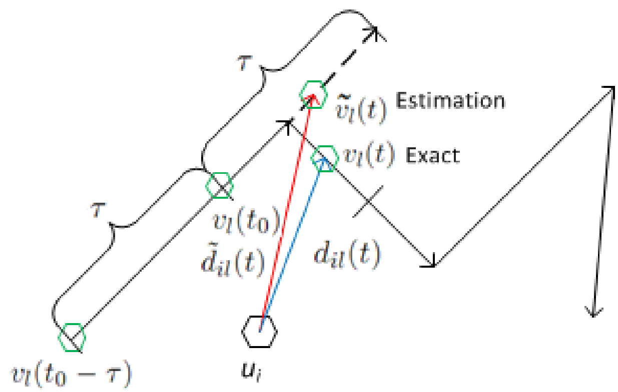


Figure 4.6: PU movement pattern.

Proof. It is similar to the Theorem 1. □

Remark. *When the i-th CU is outside the protection range of all the N PUs belong to V then the CAP is equal to one, otherwise it depends on the PU inactive probability, i.e.,* P^m_{off} *which is assumed the same for all the PUs. Since the probability that the i-th CU is inside the protection range of the arbitrary PU increases when N increases, then the CAP in the MPC scenario is lower than the SPC scenario.*

4.4.3 Trade-off between the temporal updating interval τ and distance estimation error

It is worth noticing that the larger is τ, the smaller is the updating rate of the PU position, i.e., the lower is the network overhead and and energy consumption. However, the estimation of the distance for the next temporal period becomes less accurate. We explain this concept with an example, as shown in Fig. 4.6. Here, the non-dashed line is the exact PU movement pattern, and $v_l(t)$ and $\tilde{v}_l(t)$ represent the exact and estimated PU position at time t, respectively. Since the distance at time t is estimated assuming that the PU does not change its velocity and direction during the interval $[(t_0-\tau),(t_0+\tau)]$, the estimation procedure will encounter an error when the PU changes these parameters during this interval. In particular, when τ increases, the error increases as well, and it has an impact on the accuracy of the estimation model which can be assessed in terms of Root Mean Square Error (RMSE). We can see from the Fig. 4.7 that the RMSE increases with the increasing value of τ.

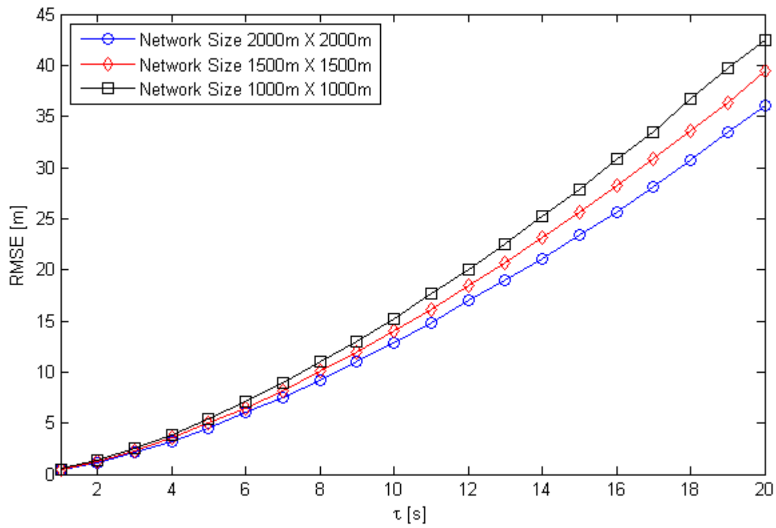


Figure 4.7: RMSE versus τ in terms of network size.

In particular, the RMSE increases when the network size decreases, since the smaller is the network size, the greater is the frequency that the PU change its direction, in according to the random waypoint mobility model [109]. In Section 4.6, we will assess the impact of τ on the estimation of the CAP.

4.5 Mobility-Aware Channel-Availability Based Channel Selection Technique

In this section, we discuss about the proposed Mobility-aware Channel-Availability based channel Selection Technique (MCAST). Based on the estimation model derived in the previous section, the CU selects the best channel with the highest value of the estimated CAP averaged over the next temporal period $[t_0, t_0 + \tau]$, as follows:

$$m_{\text{opt}}^{\text{SPC}} = \arg\max_m \tilde{q}_{il}^m(t_0, \tau) = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \tilde{p}_{il}^m(t)dt \tag{4.13}$$

$$m_{\text{opt}}^{\text{MPC}} = \arg\max_m \tilde{q}_{iV}^m(t_0, \tau) = \frac{1}{\tau} \int_{t_0}^{t_0+\tau} \tilde{p}_{iV}^m(t)dt \tag{4.14}$$

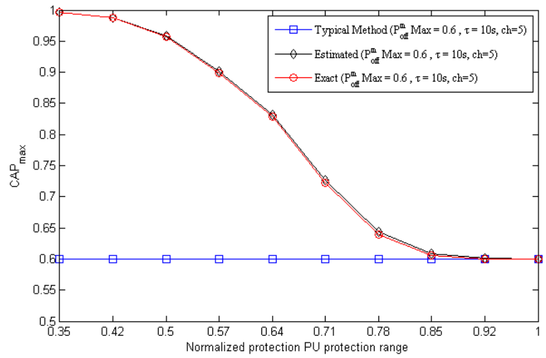
where $\tilde{q}_{il}^m(t_0, \tau)$ ($\tilde{q}_{iV}^m(t_0, \tau)$) denotes the estimated CAP averaged on $[t_0, t_0 + \tau]$ in the SPC (MPC) scenario, that depends on the actual instant of time t_0 and the period τ. This probability equals to one when the estimated distance during $[t_0, t_0 + \tau]$ is greater then the protection range, it is equal to P_{off}^m when the estimated distance is less than or equal to the protection range, while it is comprised between one and P_{off}^m in the intermediate case. Thus, by exploiting the dynamic variation of the channel availability caused by the PU mobility, the proposed technique is able to outperform the typical method that considers only the PU temporal activity. The simulation results in Section 4.6 highlight the benefits of using the proposed technique for selecting a channel in presence of PU mobility.

4.6 Simulation Results

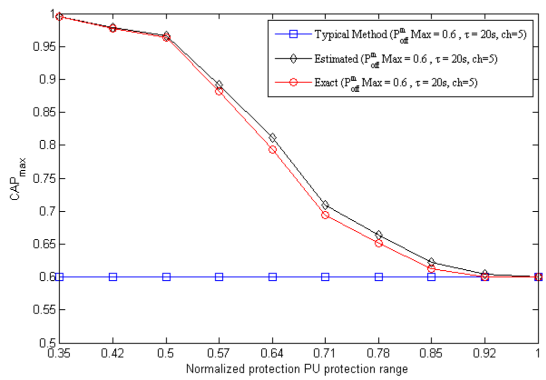
In this section, first we evaluate via numerical experiments the performance of the proposed channel selection technique (MCAST). Then we prove its effectiveness by adopting MCAST in a routing metric, recently proposed in literature [102], referred to as OPERA.

4.6.1 Performance evaluation

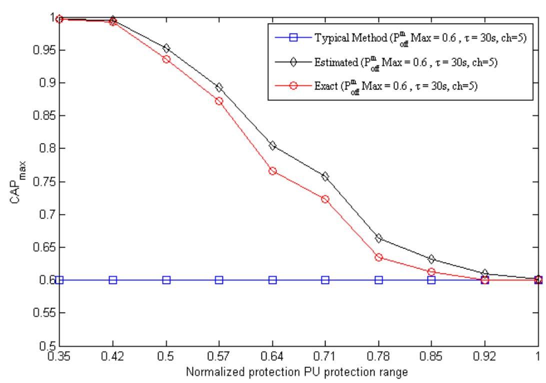
Fig. 4.8 shows the performance comparison between the *mobility-aware method* (MCAST) and the *typical method* in terms of maximum CAP ($\mathrm{CAP}_{\max}$), i.e., every τ seconds we consider the maximum CAP achievable from the best selected channel among the others, then we average it over the total number of periods considered in the simulation. It is plotted the exact and the estimated $\mathrm{CAP}_{\max}$ in the SPC scenario, along with the $\mathrm{CAP}_{\max}$ corresponding to the typical method, versus the normalized PU protection range where $R_{il} = \{500m, 600m, 700m, ..., 1400m\}$. The adopted simulation set is defined as follows: the CU transmission range is $T_i = 100m$, CU interference range is $I_i = 200m$, the PU transmission range is $T_l = 300m$, the number of channels is $M = 5$, the PU inactive probability vector is $\{0.6, 0.2, 0.3, 0.5, 0.4\}$, the PU spectrum occupancy model is SPC, i.e., each channel is used by a single PU. The PUs move in a square region of side $a = 2000m$ according to the RWPM model, where the minimum velocity is $v_{min} = 5m/sec$ and maximum velocity is $v_{max} = 10m/sec$.



(a) Temporal period $\tau = 10$s.



(b) Temporal period $\tau = 20$s.



(c) Temporal period $\tau = 30$s.

Figure 4.8: Maximum CAP vs normalized PU protection range, SPC scenario.

In Fig. 4.8 (a), we note that there is a very good agreement between the estimated and exact $\mathrm{CAP}_{\max}$ when $\tau = 10s$. The $\mathrm{CAP}_{\max}$ decreases in both the methods when the PU protection range increases, and achieves the minimum value (given by the typical method) when the normalized PU protection range is equal to one. This is reasonable because the greater is the protection range, the lower is the percentage of time in which the PUs are outside the protection range. For the typical method, the $\mathrm{CAP}_{\max}$ is always 0.6 since it selects the channel according to the maximum PU inactive probability P^m_{off}.

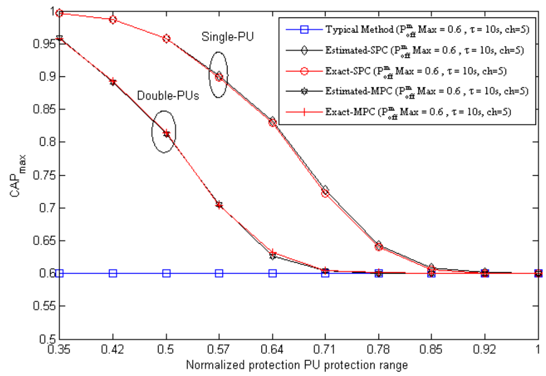
In Fig. 4.8 (b, c), we note that the average error of the estimated $\mathrm{CAP}_{\max}$ increases by increasing τ. This is because in the estimation model we assume that the PU does not change its velocity and direction during the interval $[(t_0 - \tau), (t_0 + \tau)]$. This error have an impact on the performance evaluation that means a trade-off between the effectiveness for the spectrum utilization and network overhead caused by the updating PU position mechanism.

In Fig. 4.9, we consider the MPC scenario, i.e., each channel is used by multiple PUs. The adopted simulation set is the same defined in Fig. 4.8, but we consider two PUs for each channel. We compare the $\mathrm{CAP}_{\max}$ in the SPC and MPC scenarios. Specifically, we note that the $\mathrm{CAP}_{\max}$ in the MPC scenario is lower than the SPC scenario. This is reasonable because, according to Theorem 2, the probability that the CU is inside the protection range of the PU increases when there are more PUs for each channel. The same considerations about the estimation model drawn for the SPC scenario are valid for the MPC scenario.

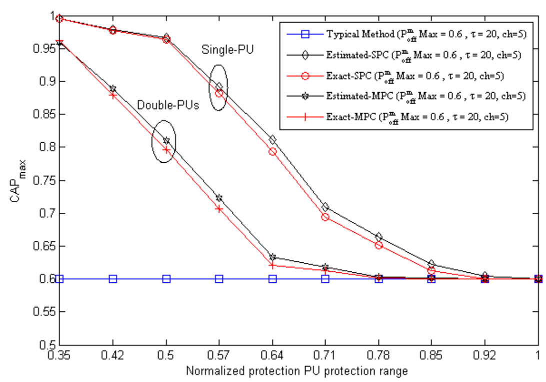
4.6.2 Effectiveness

In this subsection, we evaluate the effectiveness of MCAST in a scenario of practical interest. Specifically, we adopt MCAST in a recently proposed routing metric designed for CRNs, referred to as OPERA, and analyze the network performance in terms of packet delay.

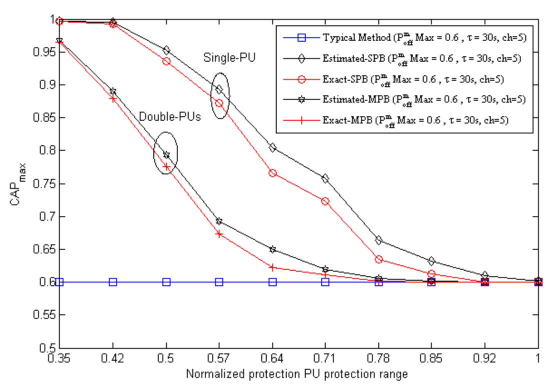
The network topology is shown in Fig. 4.10 and it is similar to the one used in [75], with 64 CUs spread in a square region of side 1000m. The CU transmission standard is IEEE 802.11g, the packet length is L = 1500 bytes, the expected link throughput is $\bar{\psi} = 54$Mbps, the transmission range of CU is equal to 200m, the transmission range of PU is equal to 166m and the number of channels is M = 2. Unlike the experiment in [75], we assume that the PUs are mobile and they are moving according



(a) Temporal period τ = 10s.



(b) Temporal period τ = 20s.



(c) Temporal period τ = 30s.

Figure 4.9: Maximum CAP vs normalized PU protection range, SPC vs MPC scenario.

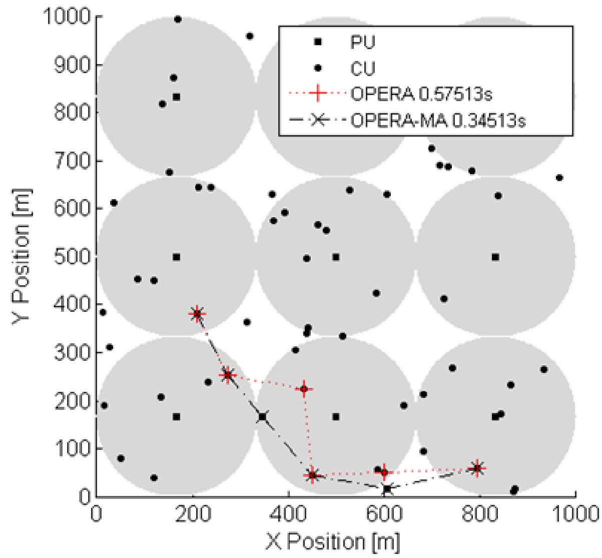


Figure 4.10: Effectiveness: Two different routes and the respective delays between the same pair source-destination, the routes singled out by OPERA and OPERA with Mobility-Aware method (OPERA-MA).

to the RWPM.

Fig. 4.10 shows two different routes with the same source and destination, and one of them that refer to OPERA with the proposed mobility-aware method (OPERA-MA). In the case of OPERA, where the typical channel selection method is utilized, the delay is 0.57s. On the other hand, in the case of OPERA-MA we observe that the delay is significantly decreased to 0.34s.

In Fig. 4.11, for both the cases we report the packet delay versus the distance between source and destination nodes. First, we observe that the delay computed by both OPERA and OPERA-MA increases with the distance. This result is reasonable, because the longer is the path, the more is the number of PUs affecting it. However, we observe that OPERA-MA exhibits a significant improvement compared to OPERA when the distance increases, since more favorable paths are available by accounting for PU mobility.

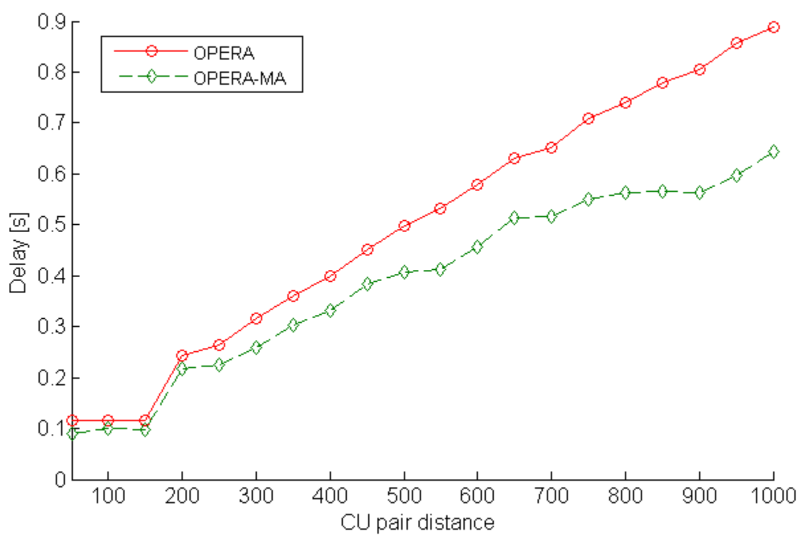


Figure 4.11: Effectiveness: Delay vs. CU pair distance for OPERA and OPERA-MA.

Symbols	Descriptions
$u_i(t)$	Position of an arbitrary i-th CU at time t
$v_l(t)$	Position of an arbitrary l-th PU at time t
P^m_{off}	The probability that PU is inactive on channel m
$p^m_{il}(t)$	The probability that at time t the channel m is available for the transmission of the *i-th* CU without causing interference to the communication of the *l-th* PU
R_{il}	Protection range of l-th PU
I_i	Interference range of i-th CU
T_l	Transmission range of l-th PU
$d_{il}(t)$	Distance between i-th CU and l-th PU at time instant t
$\tilde{p}^m_{il}(t)$	The estimated probability that at time t the channel m is available for the transmission of the *i-th* CU without causing interference to the communication of the *l-th* PU
$\tilde{d}_{il}(t)$	Estimated distance between i-th CU and l-th PU at time instant t
$d_{il}(t_0 - \tau)$	Distance between i-th CU and l-th PU at time instant $(t_0 - \tau)$
$d_{il}(t_0)$	Distance between i-th CU and l-th PU at time instant t_0
$\tilde{\theta}_{il}(t_0 - \tau)$	Estimated movement direction of l-th PU towards i-th CU at time instant $(t_0 - \tau)$
s	It is the distance traveled by l-th PU at the time interval $[t_0 - \tau,\, t_0]$
$s'(t)$	It is the distance traveled by l-th PU at the time interval $[t_0,\, t]$
$\tilde{p}^m_{iV}(t)$	The probability that i-th CU does not interfere with the communications of V set of PUs through the *m-th* channel at time instant t
τ	The PU position updating interval
$\tilde{q}^m_{il}(t_0, \tau)$	The estimated CAP averaged on next updating interval τ in the SPC scenario
$\tilde{q}^m_{iV}(t_0, \tau)$	The estimated CAP averaged on next updating interval τ in the MPC scenario

Table 4.1: Symbols used for Estimation Method

Conclusions and Future Works

Cognitive Radio (CR) is considered the enabling technology of the Dynamic Spectrum Access (DSA) paradigm which is envisaged to solve the spectrum scarcity problem, thus facilitating the accommodation of new wireless services as well as providing an effective solution to the ever increasing user demand. The main objective of this thesis is to address the routing problem under the challenging scenario characterized by the uncertain availability of the spectral resource. The routing problem is furthermore challenging in presence of PU mobility. To deal with this scenario, we proposed to utilize jointly path and spectrum diversity in routing to assure an improved spectral efficiency. We also proposed a mobility-aware channel-availability based channel selection technique, which performs the best channel selection in terms of spectrum availability in presence of PU mobility. In the following we discuss the main contributions of this thesis:

- *An overview of Cognitive Radio paradigm;*
- *A routing overview of the Cognitive Radio Ad-Hoc Networks (CRAHNs);*
- *Joint Path and Spectrum Diversity in Routing for efficient use of spectrum in CRAHNs;*
- *Mobility-aware channel-availability based channel selection technique to perform the best channel selection in terms of spectrum availability in presence of PU mobility.*

Firstly, it has been presented the overview of CR paradigm by providing the general discussion about DSA paradigm, CR technology, CR

Networks (CRNs); in particular CRAHNs due to their challenging features, which derive from the absence of the network infrastructure. It has been also presented the routing overview of CRAHNs, since the routing issue on this networks is an emerging research area.

In this thesis, it has been proposed a novel routing protocol for CRAHNs referred to as Dual Diversity Cognitive Ad-hoc Routing Protocol (D^2CARP). Such a protocol addresses the routing problem under the challenging scenario characterized by the uncertain availability of the spectral resource. To deal with this scenario, it has been proposed to exploit the joint path and spectrum diversity to counteract the performance degradation experienced by CUs due to the activity of frequency- and space-varying Primary Users (PUs). To assess the effectiveness of the proposal, we have carried out a performance comparison between the proposed protocol and a recent one which does not exploit jointly path and spectrum diversity. The results confirm the effectiveness of the proposal.

Finally, we proposed a novel Mobility-aware Channel-Availability based channel Selection Technique (MCAST) for CR networks that maximizes the network performance by selecting the channel with the highest channel-availability in given temporal period. In fact, this technique takes advantage from the dynamic variation of channel-availability caused by the PU mobility and consequently outperforms the typical method which is only based on the PU temporal activity. The numerical experiments corroborate the theoretical results. Moreover, it has been evaluated the effectiveness of MCAST in a scenario of practical interest by adopting this technique in a recently proposed routing metric designed for CRNs. The simulation results reveal the benefits of introducing the proposed channel selection technique.

It is worthwhile to underline that the cross-layer issue needs to be considered for providing a routing solution in CRAHN, since it is an infrastructure-less network. However, we do not consider it in this thesis, as it is our initial stage of work in CRAHN. In our future work, we will focus on cross-layer issues and also investigate the impact of PU mobility in MAC layer.

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