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STUDY, DESIGN AND DEVELOPMENT OF NOVEL ARCHITECTURES AND TECHNOLOGIES THAT EXPLOIT THE DIGITAL SPECTRUM DIVIDEND FOR THE DEVELOPMENT OF WIRELESS LOCAL / METROPOLITAN MULTIMEDIA SERVICES INFRASTRUCTURES

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This Ph.D. Thesis is dedicated to my husband, George, for his constant support

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Περιληψη

Η Διδακτορική Διατριβή αυτή συμβάλλει στην ευκαιριακή αξιοποίηση του ραδιοφάσματος, μέσω της μελέτης, του σχεδιασμού και της υλοποίησης μίας πρωτότυπης αρχιτεκτονικής, η οποία επιτρέπει στις μη-αδειοδοτημένες (δευτερεύουσες) συσκευές να αξιοποιούν δυναμικά και σε τοπικό επίπεδο, τις διαθέσιμες τηλεοπτικές συχνότητες VHF / UHF (Τηλεοπτικό Λευκό Φάσμα - TVWS) για την παροχή πολυμεσικών υπηρεσιών σε ασύρματες τοπικές/μητροπολιτικές υποδομές. Βασιζόμενη στις πρόσφατες εξελίξεις της τεχνολογίας του γνωσιακού ραδιοφάσματος (Cognitive Radio technology) καθώς και εξετάζοντας τις νέες πολιτικές διαχείρισης του ραδιοφάσματος που θα αξιοποιηθούν για την εκμετάλλευση των απελευθερωμένων ραδιο-πόρων, η Διδακτορική Διατριβή παρουσιάζει μια υβριδική αρχιτεκτονική, για την αποδοτική διαχείριση του ραδιοφάσματος, είτε μέσω ενός μεσίτη φάσματος (Spectrum Broker), είτε μέσω τεχνικών αποφυγής παρεμβολών υπό την επίβλεψη μιας χωρικά τοποθετημένης βάσης δεδομένων (Geo-location database). Στα πλαίσια της παρούσας Διατριβής σχεδιάστηκε και υλοποιήθηκε, στο επίπεδο ζεύξης δεδομένων, ένας πρωτότυπος μηχανισμός, για την βέλτιστη διαχείριση των ραδιο-πόρων (Radio Resource Management - RRM) σε σχέση με την εγγυημένη παροχή Ποιότητας Υπηρεσίας (Quality of Service - QoS), καθώς και το μέγιστο δυνατό κέρδος των συναλλαγών. Προς την κατεύθυνση αυτή μελετήθηκαν, δύο είδη τεχνικών βελτιστοποίησης, η τεχνική λήψης αποφάσεων και η θεωρία παιγνίων, προκειμένου να αναπτυχθεί ένας νέος αλγόριθμος ικανός να παρέχει αποδοτικές λύσεις όσον αφορά τον ελάχιστο κατακερματισμό του φάσματος και το μέγιστο δυνατό κέρδος του μεσίτη φάσματος. Επιπλέον, η Διατριβή συμβάλλει στη μελέτη και ανάπτυξη ενός νέου πρωτοκόλλου δρομολόγησης, που επιτρέπει την επικοινωνία μεταξύ συστημάτων, τα οποία δημιουργούν ad-hoc γνωσιακά δίκτυα και βρίσκονται σε διαφορετικές περιοχές (δηλαδή, δεν υπάρχει άμεση ζεύξη επικοινωνίας μεταξύ τους). Για να γίνει αυτό, το βέλτιστο μονοπάτι επικοινωνίας εγκαθίσταται μέσα από μία σειρά ενδιάμεσων κόμβων που χρησιμοποιούν την γνωσιακή τεχνολογία, οι οποίοι επιλέγονται βήμα-προς-βήμα (hop-by-hop) αξιολογώντας τη χρονική καθυστέρηση της επικοινωνίας. Επιπλέον, και προκειμένου να αποφευχθούν πιθανές αποτυχίες στη διαδρομή ή υπερφόρτωση των ενδιάμεσων κόμβων, το πρωτόκολλο εφαρμόζει ένα πρωτότυπο μηχανισμό σε κάθε κόμβο, προκειμένου να εξισορροπείται το φορτίο κάνοντας ανακατεύθυνση της δικτυακής κίνησης. Για την επαλήθευση της εγκυρότητας της προτεινόμενης αρχιτεκτονικής, μία σειρά από πειράματα σχεδιάστηκαν και διεξήχθησαν υπό ελεγχόμενες συνθήκες περιβάλλοντος (προσομοιώσεις). Στα πλαίσια αυτά, ένα πειραματικό πρωτότυπο τέθηκε σε εφαρμογή σύμφωνα με τις τεχνικές προδιαγραφές σχεδιασμού, το οποίο αξιοποιήθηκε για τη διεξαγωγή μετρήσεων αξιολόγησης των επιδόσεων. Τα αποτελέσματα που προέκυψαν επαλήθευσαν την ικανότητα της προτεινόμενης αρχιτεκτονικής για την υποστήριξη της ανάπτυξης τοπικών/μητροπολιτικών υποδομών πολυμέσων μέσω της ευκαιριακής αξιοποίησης του ραδιοφάσματος των TVWS και ανέδειξαν πεδία μελλοντικής έρευνας, όπως η λειτουργία με την ελάχιστη ενεργειακή απόδοση τόσο σε επίπεδο συστημάτων όσο και τελικών χρηστών ή η μελέτη μηχανισμών επιπέδου μεταφοράς για τον περιορισμό των μειονεκτημάτων του υπάρχοντος TCP σε χρονικά μεταβαλλόμενα συνδέσεις.

ABSTRACT

This Ph.D. thesis contributes to the issue of opportunistic radio spectrum exploitation, by studying, designing and implementing a prototype architecture that enables unlicensed (secondary) devices to dynamically utilize the locally available VHF/UHF frequencies (namely the TV White Spaces – TVWS) for the provision of multimedia services over local/metropolitan wireless infrastructures. Building upon the recent advances in cognitive radio technology and by elaborating on novel spectrum management policies for liberalized resource exploitation, it presents a hybrid system architecture, where the radio resource allocation is efficiently coordinated either via a spectrum broker entity (Real-Time Secondary Spectrum Management policy) or via interference avoidance techniques assisted by a Geo-location database (Spectrum of Commons policy). The optimum Radio Resource Management (RRM) as a matter of guaranteed Quality of Service (QoS) provision and maximum possible trading revenue is carried over a prototype mechanism at the data-link layer that is designed and implemented within the framework of this thesis. Towards this, two types of optimization approaches are studied, one based on decision-making and the other one game theory concepts, and a novel algorithm is developed capable to provide minimum spectrum fragmentation and maximum possible spectrum broker utility. Furthermore, the thesis also elaborates on the study and development of a novel routing protocol, that enables inter-system communications among users/nodes, which are located in different and isolated (to each other) ad-hoc Cognitive Radio (CR) networks (i.e. no direct communication link exists between them). To do so, the optimum communication path is established through a number of intermediate CR nodes, which are selected via a hop-by-hop process by evaluating a number of delay metrics at each intermediate node level. Furthermore and in order to avoid possible route failures or overloading of the intermediate nodes, the implemented protocol utilises a prototype mechanisms at each node level, responsible for load balancing and traffic redirection. Towards verifying the validity of the proposed architecture a number of experiments were designed and conducted under controlled conditions environment (simulations). For this reason, a prototype test-bed conforming to the architectural design specifications was implemented, which also served as the experimental environment for carrying out performance evaluation measurements. The obtained results verified the capacity of the proposed architecture to support the deployment of local/metropolitan multimedia infrastructures through the opportunistic exploitation of TVWS, besides indicating fields for future research, such as energy efficient operation both at system and end-user levels, or transport layer mechanisms to mitigate the existing TCP's drawbacks in time-varying links.

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DECLARATION

Part of the contribution of this thesis has been presented in conferences and submitted and/or accepted for publication:

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2. A. Bourdena, G. Mastorakis, E. Pallis, and G. Kormentzas, "A Routing Protocol for Enhanced Efficiency in Cognitive Radio Networks", Journal of Communications and Computers, (*to appear in the forthcoming issue*).
3. A. Bourdena, E. Pallis, G. Kormentzas, and G. Mastorakis, "Efficient Radio Resource Management Algorithms in Opportunistic Cognitive Radio Networks", Emerging Telecommunication Technologies, Wiley, 29 July, 2013.
4. A. Bourdena, C. X. Mavromoustakis, G. Kormentzas, E. Pallis, G. Mastorakis, and M. B. Yassein, "A Resource Intensive Traffic-Aware Scheme using Energy-efficient Routing in Cognitive Radio Networks", Future Generation Computer Systems, Elsevier (*accepted for publication with revisions*).

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1. A. Bourdena, G. Kormentzas, M. Astrinaki, G. Mastorakis, E. Pallis, and V. Zacharopoulos, "Efficient sharing of TV White Spaces utilizing mobile TV networks with a cognitive radio approach", in Proc. International Conference on Telecommunications and Multimedia (TEMU2010), Chania, Crete, Greece, 14-16 July, 2010, pp. 102-109.
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1. A. Bourdena, P. Makris, D. Skoutas, C. Skianis, G. Kormentzas, E. Pallis, and G. Mastorakis, "Joint Radio Resource Management in Cognitive Networks: TV White Spaces Exploitation Paradigm", in the book "Evolution of Cognitive Networks and Self-Adaptive Communication Systems", Editors: T. Lagkas, P. Sarigiannidis, M. Louta, and P. Chatzimisios, June 2013, pp. 50-80.

CONTENTS

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INTRODUCTION

Background and motivation

Emerging types of wireless applications and telecommunication services, rich in user-created content with high demands for network resources and stressed end-to-end QoS requirements, put pressure on the available radio-frequencies (i.e. the fundamental resource in wireless systems), thus raising the need for frequency availability and creating new challenges in spectrum management and administration. While the utilization of advanced signal-processing techniques enables for efficient spectrum-usage – even in the traditional framework of the "command-and-control" regime – there is a worldwide recognition [1] that these methods of spectrum management have reached their limit and are no longer optimal. In fact spectrum utilization studies have shown that most of the assigned (licensed) spectrum is under-utilized [2], [3], and a considerable amount of radio-frequencies are available when both dimensions of space and time are considered. Such an example of under-utilized spectrum is the so-called "television white spaces" (TVWS), comprising VHF/UHF frequencies that are either released/freed by the digital switchover process ("Spectrum/Digital Dividend"), or totally unexploited (mainly at the local level) due to frequency planning issues and/or network design principles ("Interleaved Spectrum") [4]. TVWS usually sum up-to tenths of MHz at the local/regional level [5], facilitate low cost and low power system design, provide superior propagation conditions and building penetration, while at the same time their sufficiently short wavelength allows for the construction of resonant antennas at a size and shape that is acceptable for many mobile devices. Therefore, TVWS are well-suited for wireless applications and mobile telecommunication systems. However, the current "command-and-control" regime allows only primary (licensed) systems to exploit these TVWS for the provision of primary services, such as terrestrial digital video broadcasting (DVB-T), handheld digital video broadcasting (DVB-H), interactive TV (iTV), Programme Making and Special Events (PMSE), while prohibiting any other secondary transmission. Hence, the problem of spectrum scarcity, as perceived today, is one of inefficient frequency management rather than of spectrum shortage. The envisioned schemes include liberalised policies [6] so that secondary (unlicensed) systems are allowed to opportunistically utilize the underused primary TV channels and state-of-the-art technologies for interference-free operation with primary systems.

Such an opportunistic TVWS exploitation can be based on Cognitive Radio (CR) technologies [7], [8], [9], enabling the deployment of frequency-agile devices that can identify TVWS (either by themselves via spectrum sensing or by a Geo-location data-base) and adapt their transmission characteristics so that licensed (primary) users are not interfered. To achieve these, CR networks are exploiting architectures that can be characterized as a) infrastructure-based or ad-hoc, depending on the frequency/rate that the network topology changes, b) single-hop or multi-hop, depending on the communication between a transmitter and a receiver, and c) centralized or distributed if the decision of spectrum access is made by a central controller/module or locally by each individual frequency-agile device [10]. The common element among these architectures is the radio resource management process (RRM) [11], [12], [13], i.e. a data-link layer mechanism responsible for dynamically allocating the available TVWS, as a matter of the service/application characteristics (e.g. QoS requirements, time and duration of TVWS exploitation, geographical attributes, mobile or fixed access, etc.). Existing RRM implementations, as proposed in [10], [14], fall within two main categories of optimization algorithms: a) the decision making algorithms, which are trying to reach an optimal solution through classical mathematical rationalization, and b) game theory algorithms that view radio-resource optimization as a multi-objective optimization problem and model it as a game between primary and secondary systems with incentives to conflict or to cooperate. The former are based on formulating an objective function (i.e. the goal of the optimization), as well as on setting equality and inequality constraints that the optimal solution must not cross [10], and comprise three groups of solutions, i.e. closed form solution, integer/combinatorial programming and mathematical programming. On the other hand, the game theory approach is based on the formulation of equilibrium criteria, in order to evaluate game optimality, using two fundamental concepts, i.e. the Nash equilibrium and the Pareto optimality [10].

Since the introduction of CR networks in TVWS represents a disruption to the current "command-and-control" spectrum management paradigm, RMM is highly intertwined with the regulation models [15] that would eventually be adopted. Among the envisaged regulation models are the "Spectrum of Commons" (or unlicensed policy) and the "Real-time Secondary Spectrum Market" (or licensed policy). The Spectrum of Commons represents the case where coexistence of secondary systems with incumbent primary transmissions (e.g. Digital Video Broadcasting – Terrestrial (DVB-T)) is assured via the control of the interference levels rather than by a fixed spectrum assignment. To do this, in the Spectrum of Commons model, secondary systems exploit sensing techniques for reliable detection of TVWS and coexistence mechanisms for interference avoidance. In a "Spectrum of Commons" usage model there is no spectrum manager to preside over the resource allocation, and, therefore, ad-hoc and de-centralised architectures are the most promising implementations. In this context, RRM is an autonomic process, among the corresponding CR network players, similarly to the wireless ISM (Industrial Scientific and Medical) bands where users have to fulfil the technical rules ensuring good coexistence, but do not need to negotiate with existing players. However, despite the fact that Spectrum of Commons promotes fairness, efficiency in term of QoS cannot be guaranteed, thus posing serious problems especially for QoS-sensitive applications. Additionally, while intra-system communication can be effectively accommodated, inter-system networking constitutes a major issue for the Spectrum of Commons model, mainly when the communicating CR devices are placed over highly heterogeneous/dispersed TVWS allotments. More specifically, the intra-system communication may be based on conventional routing protocols that utilise network-wide broadcast messages over a Common Control Channel (CCC), without using any local hop information, towards improving the choice of optimum routing paths. Since such Common Control Channels are not available among CR devices located in heterogeneous/dispersed TVWS allotments, inter-system networking requires more sophisticated network-layer mechanisms (i.e. routing protocols) that provide for "spectrum mobility" prior to establishing and maintaining a routing path among the secondary communication nodes.

In order to promote efficiency (instead of fairness) and avoid the "tragedy of the commons" [16], spectrum policies that are based on etiquette rules come to the foreground. The "Real-Time Secondary Spectrum Markets" (RTSSM) arises as one the most appropriate solutions, especially for applications that require sporadic access to spectrum and for which QoS guarantees are important. Contrary to the Spectrum of Commons, in the RTSSM policy coexistence of secondary systems with incumbent primary transmissions (e.g. DVB-T) is assured via fixed spectrum assignment rather than by control of interference levels. This is achieved through a spectrum trading process, which allows primary users (license holders) to sell/lease spectrum usage rights and secondary players to buy them (license vendees), thereby establishing a secondary market for spectrum leasing and spectrum auction. The license holder runs an admission control algorithm, which allows secondary users to access spectrum only when the QoS of both primary and secondary are adequate. Evidently, infrastructure-based and/or centralised architectures are the most promising implementations in the RTSSM model. The trading of secondary use may also occur through intermediaries such as a spectrum broker that is responsible for exploiting spectrum resource management algorithms in order to determine the frequency at which a secondary user should operate. Secondary users dynamically request access (from the central node) when-and-only-when spectrum is needed and are charged based on a spectrum utilization basis, as a function of type of services, access characteristics, and QoS level requests. The access types could consist of a long-term lease, a scheduled lease, and a short-term lease or spot markets. Each type requires different resource discovery mechanisms and applies with different levels of service agreements. It should be also noted that apart from carrying out the spectrum trading processes, a broker may also assist in inter-system communication by exploiting appropriate mechanisms at the network-layer, thus alleviating the need for sophisticated routing protocols even in the case that the CR devices are placed over highly heterogeneous allotments. However, such implementations call-for complicated broker configurations, mainly at the network and transport layers, capable to handle the different communication and signalling protocols exploited by each communicating CR system; an issue that raises the complexity of the overall architecture and poses scalability challenges.

Aim of the Research and Contribution

Taking into account the pros and cons of each regulation model, the aim of this doctoral thesis is the implementation of a unified spectrum management framework, where both fairness and efficiency can be inherently supported. The challenge is the study, design and implementation of a hybrid system architecture and the corresponding data-link mechanisms (RRM) that can optimally allocate the available TVWS among diversified network configurations, along with the appropriate network-layer mechanisms (i.e. routing protocols), which may allow for intra- and inter-system communication, even among CR devices that are placed over highly heterogeneous/dispersed TVWS allotments.

In this context, this thesis describes a centralised cognitive radio network, where the dynamic TVWS allocation among various secondary systems is coordinated by a spectrum broker, following the RTSSM policy, while the intra-system radio resource management is based on the Spectrum of Commons model. The spectrum broker administers the economics of TVWS leasing, either via fixed-price or auction-based transactions. For efficient system performance, as a matter of maximum-possible radio resource exploitation and/or trading revenue, the thesis elaborates on the design and implementation of a prototype RRM framework at the spectrum broker side. Towards this, an RRM algorithm was designed, developed and incorporated in the proposed centralized CR networking architecture, enabling for efficient TVWS exploitation as a matter of secondary systems' QoS requirements either by minimizing spectrum fragmentation or by maximizing spectrum broker profit. Experimental tests verified the capability of this novel algorithm to optimally allocate TVWS among secondary systems in the proposed architecture, as well as to respect and fulfil certain QoS requirements. In this sense, it is anticipated that the proposed CR network architecture can be adopted by cellular network operators, taking advantage of TVWS propagation characteristics to cover large geographical areas with a smaller number of base stations (and, therefore, with lower cost), and offering mobile broadband services at lower prices to more consumers, especially in rural areas. Additionally, it is anticipated that in dense urban areas, the proposed architecture can be used for TVWS exploitation on a temporary basis for support at peak hours load (e.g. short or medium term spectrum leasing), in order to provide relief for crowded primary networks/frequencies, whenever these are overloaded.

In order to achieve efficient intra- and inter-system communication, the thesis also elaborates on the study, development and experimental evaluation of a novel routing protocol, allowing the communication among secondary users (i.e. CR devices) even when these are located in dispersed and isolated TVWS allotments. More specifically, the proposed routing scheme is designed for ad-hoc CR constellations (i.e. TVWS assignment is also assisted by a Geo-location database), where each communicating party is placed at different/isolated TVWS allotments and no direct communication link exists between the corresponding CR users. For these reasons, the proposed routing protocol encompasses mechanisms that take into account the system topology (in an end-to-end approach) prior to establishing the best routing path. Traffic redirection, in case of route failure in the path, and load balancing are also utilised at each secondary user level, for determining which neighbouring node performs better in the routing path, or for mitigating traffic in cases of overloading. It should be also noted that in the proposed hybrid architecture the broker may also assist in inter-system communication, acting as a traffic coordinator among all underlying CR systems. However, such an approach calls-for more complex configurations at the broker side, which are beyond the scope and the aims of this thesis.

Structure of the Thesis

Following this introductory chapter, the rest of this thesis is structured as follows:

Chapter 1 discusses the radio-frequencies that are available in VHF/UHF bands, which constitute the so-called TVWS radio spectrum, and reviews existing CR technologies and potential spectrum management policies for their exploitation by secondary devices/users. It initially studies network architectures and configurations of CR system implementations, and delves into the main CR functionalities allowing for spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. The chapter also discusses the issue of command-and-control regime and elaborates on potential spectrum management frameworks that allow for a liberalised exploitation of TVWSs, based either on the Spectrum of Commons or on the Real Time Secondary Spectrum market policies. Finally, the chapter presents a number of technological issues that may provide for efficient radio resource management and exploitation (i.e. RRM at the data-link layer), as well for optimum communication and efficient data routing among secondary users (i.e. routing protocols at the network layer).

Chapter 2 discusses the design of a prototype hybrid CR networking infrastructure capable to support opportunistic TVWS exploitation by unlicensed users both in infrastructure-based and ad-hoc deployments, and elaborates on the design and implementation of the corresponding data-link layer mechanisms, which can efficiently allocate the available radio resources as a matter of services' QoS requirements and economic/trading aspects. In this context, it elaborates on the study and development of a centralized CR network architecture, where a spectrum broker administrates the available TVWSs via radio resource management mechanisms, which are based either on decision making algorithms or game theory ones. Furthermore, and to achieve efficient support of ad-hoc CR networking constellations, the proposed architecture is complemented by a Geo-location spectrum database, assisting the interference-free operation of secondary devices in the presence of primary incumbent systems.

Chapter 3 presents the performance evaluation based on implementation and realisation of a prototype that conforms to the architectural design, and which serves as a testbed for conducting simulation experiments. It presents the performance evaluation of a Radio Resource Management and Trading framework that enables TVWS trading under the RTSSM policy, besides enabling guaranteed QoS provision as a function of maximum transmission power and interference thresholds. Towards establishing the validity of the proposed architecture, the chapter analyses the performance experimental results, both for fixed-price spectrum trading (as a function of spectrum fragmentation, spectrum utilization and simulation time) and for the auction-based spectrum leasing (as a function of spectrum broker benefit/utility, spectrum fragmentation, spectrum utilization and probability of accessing TVWS).

Chapter 4 presents the design and implementation of a novel routing protocol (i.e. network-layer process) that alleviates the issue of data communication among secondary users of ad-hoc CR networks, which are located in dispersed and isolated (to each other) TVWS allotments. In this context, the chapter discusses the design and implementation of a novel routing protocol that can achieve the optimal path between two communicating users/nodes, through the evaluation of specific delay metrics in a hop-by-hop process (i.e. switching, queuing and backoff delay) prior to establishing the end-to-end route. In case that a user/node cannot establish the next hop or in cases that an established end-to-end link is broken, the proposed routing protocol redirects data traffic by finding alterative paths. Finally, and towards enhancing the overall performance of the proposed routing protocol in the presence of heavy loaded intermediate nodes (i.e. those participating in the end-to-end path), the chapter presents the design and the implementation of a load balancing mechanism (present at each node level), capable to determine the next hop as a function of the neighbouring nodes' available resources.

The last chapter of this thesis, Chapter 5, concludes by summarising the scientific findings and research results, and elaborates on fields for future exploitation.

1. RESEARCH MOTIVATION AND RELATED WORK

1.1. Introduction

Emerging CR network infrastructures are being researched and developed in response to the current wireless networks' needs for increased spectrum availability and better exploitation of the available radio resources. The deployment of CR networks can satisfy/fulfil the increasing user demands for bandwidth-hungry and QoS-sensitive services, by enabling dynamic access to the available spectrum pool along with on-demand utilisation of radio resources. Such networks are based on spectrum-agile devices that are able to adapt their transmission/reception characteristics (i.e. operating spectrum, modulation, transmission power and communication technology) based on interactions with the surrounding spectral environment. They can sense a wide spectrum range, identify dynamically locally unused frequencies and adjust their operation (e.g. frequency band, transmit power and modulation scheme) by exploiting Radio Recourse Management algorithms. This capability also opens up the possibility of designing dynamic spectrum access strategies/policies with the purpose of opportunistically reusing any under-utilised spectrum at the local level. A major obstacle, however, towards such opportunistic spectrum exploitation by CR networks is the current management framework (namely the command-and-control regime), that allows only licensed/Primary systems to operate in specific frequency bands, while prohibiting any other unlicensed (secondary) transmission. This chapter reviews the state-of-the-art concerning CR network architectures, configurations and potential policies for introducing them in licensed bands (i.e. TVWS), while it also elaborates on a number of technological challenges that may provide efficient exploitation of the available radio resources (i.e. RRM at the data-link layer), as well optimum communication and efficient data routing among secondary users (i.e. routing protocols at the network layer).

1.2. Television White Spaces - TVWS

The transition from analogue to digital terrestrial television (i.e. the Digital Switchover - DSO) [17] - [20] will be completed in EU countries by2015 [21], adopting the DVB-T standard [22] for the provision of audio-visual content. Due to the spectrum efficiency of digital terrestrial television, a number of spectrum bands used for analogue TV will be available to be for other usage. Moreover, the digital television spectrum allocation is such that there are a number of TV frequency bands, which are left unused within a given geographical location, so as to avoid causing interference to co-channel or adjacent channel transmitters (i.e. spectrum bands are geographically interleaved). These frequencies, that are completely unexploited (especially at the local level [5]) due to frequency planning issues and/or network design principles, are known as "Interleaved Spectrum" [4], while frequencies that are released or remain "leftover" by the digital switchover process are known as "Digital Dividend" [17] - [29]. Television White Spaces (TVWS) consist both of Interleaved spectrum, and Digital Dividend spectrum. TVWS usually sum up-to tenths of MHz at the local/regional level, facilitate low cost and low power system design, and provide superior propagation conditions and building penetration, while at the same time their sufficiently short wavelength allows for the construction of resonant antennas at a size and shape that is acceptable for many mobile devices. For instance, a potential exploitation of TVWS as shown in Fig. 1-1, can be performed by a cognitive radio network, which defines the white spaces in the coverage area between broadcasting services. On any given frequency channel, there will be a geographical zone where the use of high-power broadcasting will not be possible because of the interference it would cause, but the use of low\moderate power applications would be possible, provided these are carefully designed so as to be compatible with the primary users (e.g. digital terrestrial television) and/or other secondary users such as PMSE (Programme Making and Special Events). Moreover, several studies and results show that white spaces are present and fragmented [8]. They are typically more abundant in rural areas with larger contiguous blocks of unused channels available, as broadcast network planning priorities are linked to population density.

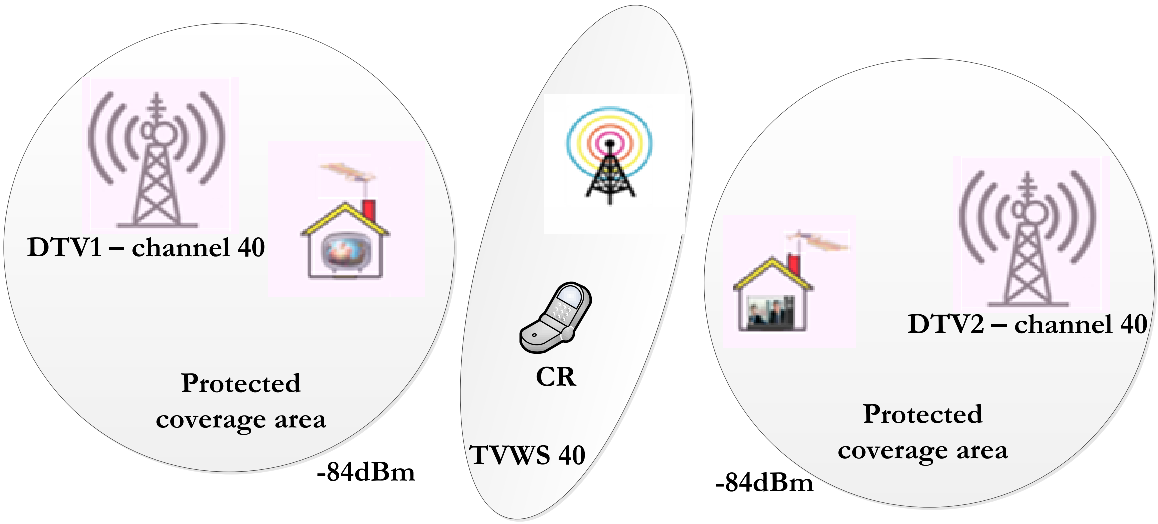

Fig. 1-1 A Cognitive Radio network operating in a Television White Space (channel 40)

1.3. Cognitive Radio Network Principles

Towards exploiting TVWS, state-of-the-art wireless technologies are required, allowing for the opportunistic and dynamic exploitation of any available spectrum in the VHF/UHF bands, which are traditionally utilized in a static manner by primary/licensed systems (e.g. DVB-T/H). In this context, a critical technical requirement among the envisaged schemes is their ability for interference-free operation with incumbent transmissions (licensed users or unlicensed ones). Towards this direction, recent research efforts and technological solutions have resulted in the development of Cognitive Radio technology, i.e. a new communication paradigm for wireless communication systems, which aims to opportunistically exploit any available (in time and space) radio frequencies. Cognitive radio provides mechanisms for intelligent spectrum sensing, spectrum management, and spectrum access for cognitive radio users (e.g. unlicensed users). The term "cognitive radio" was defined in [30] as follows: "*Cognitive radio is an intelligent wireless communication system that is aware of its ambient environment. This* *cognitive radio will learn from the environment and adapt its internal states to statistical variations in the existing* RF *stimuli by adjusting the transmission parameters (e.g. frequency band, modulation mode, and transmit power) in real-time and [in an] on-line manner*." In a cognitive radio network two types of users exist, licensed or primary and unlicensed or secondary. Primary users (e.g. DVB-T transmitters) are the incumbent systems of the spectrum band of UHF/VHF that exploit the licensed operation under the current spectrum policy (i.e. command-and-control). On the other hand, secondary users can operate in the absence of primary ones or in cases that they do not cause interference to nearby licensed users. Thus, sophisticated spectrum sensing and management methods are required, and new spectrum policies have to be adopted in order to permit the opportunistic operation of unlicensed users. A cognitive radio network enables the establishment of communication among cognitive radio nodes/users. Related communication parameters can be adjusted according to the changes in the environment, topology, operating conditions, or user requirements [31]. The two main objectives of cognitive radio are: (1) to achieve highly reliable and highly efficient wireless communications, and (2) to improve the utilization of radio spectrum.

1.3.1. **Functions of Cognitive Radio based on Cognition Cycle**

The main attribute of a CR network is that in every action it depends on its local observations. In this respect, CR networks require spectrum-aware operations in order to adapt their transmission/reception mode according to the dynamic spectrum environment. In other words, CR access and exploitation of any locally available spectrum depends on a number of processes, interrelated and intimately tied-up, altogether constituting the so-called cognitive/cognition cycle [30], [32], [33], [34], [62]. As shown in Fig. 1-2, the steps of the cognitive cycle consist of four spectrum management functions: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility [34].

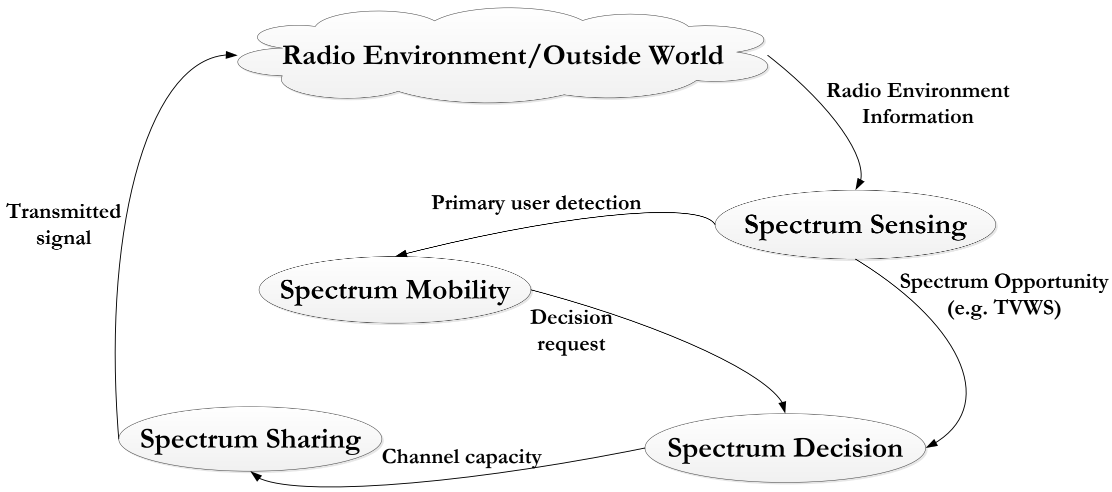

Fig. 1-2 Cognition cycle

The CR device senses the surrounding environment in order to detect unused spectrum opportunities, while it avoids the primary transmissions by requesting to switch to another frequency. Then, the spectrum decision is made by reading the spectrum allocation, while the spectrum sharing function undertakes the channel allocation based on its capacity. Finally, the action of spectrum sharing is made known to the radio environment. To implement a CR network, each function needs to be incorporated into the classical layering protocols, as shown in Fig. 1-3. In the following we briefly present the main functions of a CR network:

- Spectrum sensing: The goal of spectrum sensing, that occurs in the physical layer, is to determine the status of the spectrum and the activity of the licensed users, by periodically sensing the target frequency band. In particular, a cognitive radio transceiver detects the existence of unused spectrum or TVWS (i.e. band, location, and time) and also determines the method of accessing it (i.e. transmit power and access duration) without interfering with the transmission of a licensed user. A CR user can be allocated to only an unused portion of the spectrum. Therefore, a CR user should monitor the available spectrum bands, and then detect spectrum holes. Spectrum sensing is a basic functionality in CR networks, and hence it is closely related to other spectrum management functions as well as to layering protocols to provide information on spectrum availability.

- Spectrum Management: The unlicensed users exploit information obtained from spectrum sensing to schedule and plan spectrum access. In this case, the communication requirements of unlicensed users are also used to optimize transmission parameters. Major components of spectrum management are spectrum analysis and spectrum decision/access optimization.

  - Spectrum analysis: In spectrum analysis, information from spectrum sensing is analysed to gain knowledge about the TVWS spectrum (e.g. interference estimation, duration of availability and probability of collision with a licensed user due to a sensing error). Then, a decision to access the spectrum (e.g. frequency, bandwidth, modulation mode, transmit power, location, and time duration) is made by optimizing the system performance given the desired objective (e.g. maximize the throughput of the unlicensed users) and constraints (e.g. maintain the interference caused to licensed users below the target threshold).

  - Spectrum decision/access: Once a decision is made on spectrum decision/access based on spectrum analysis, the unlicensed users access the available spectrum. The CR users select the most appropriate band (e.g. UHF/VHF) according to their QoS requirements. It is important to characterize the spectrum band in terms of both the radio environment and the statistical behaviour of the primary users. In order to design a decision algorithm that incorporates dynamic spectrum characteristics, the primary user activity through sensing is essential. The spectrum decision/access is performed based on a cognitive medium access control (MAC) protocol, which intends to avoid collisions with licensed users and unlicensed users. The cognitive radio transmitter is also required to perform negotiation with the cognitive radio receiver to synchronize the transmission so that the transmitted data can be received successfully. A cognitive MAC protocol could be based on a fixed allocation MAC (e.g. FDMA, TDMA, CDMA) or on a random access MAC (e.g. ALOHA, CSMA/CA) [35].

- Spectrum sharing: Since there may be multiple CR users trying to access the spectrum at the same time, their transmissions should be coordinated to prevent collisions in overlapping portions of the spectrum. Spectrum sharing provides the capability to share the spectrum resource opportunistically with multiple CR users, which including resource allocation to avoid interference caused to the primary network. To do this, spectrum sharing exploits RRM algorithms implemented by decision making, as well as game theoretical approaches that can be used to analyse the behaviour of selfish CR users in order to obtain the spectrum allocation pattern.

- Spectrum mobility: Spectrum mobility is a function related to the change of operating frequency band of cognitive radio users. When a licensed user starts accessing a radio channel which is currently being used by an unlicensed user the unlicensed user can change to a spectrum band which is idle. This change in operating frequency band is referred to as spectrum handoff. During spectrum handoff, the protocol parameters at the different layers in the protocol stacks have to be adjusted to match the new operating frequency band. Spectrum handoff must try to ensure that the data transmission by the unlicensed user can continue in the new spectrum band.

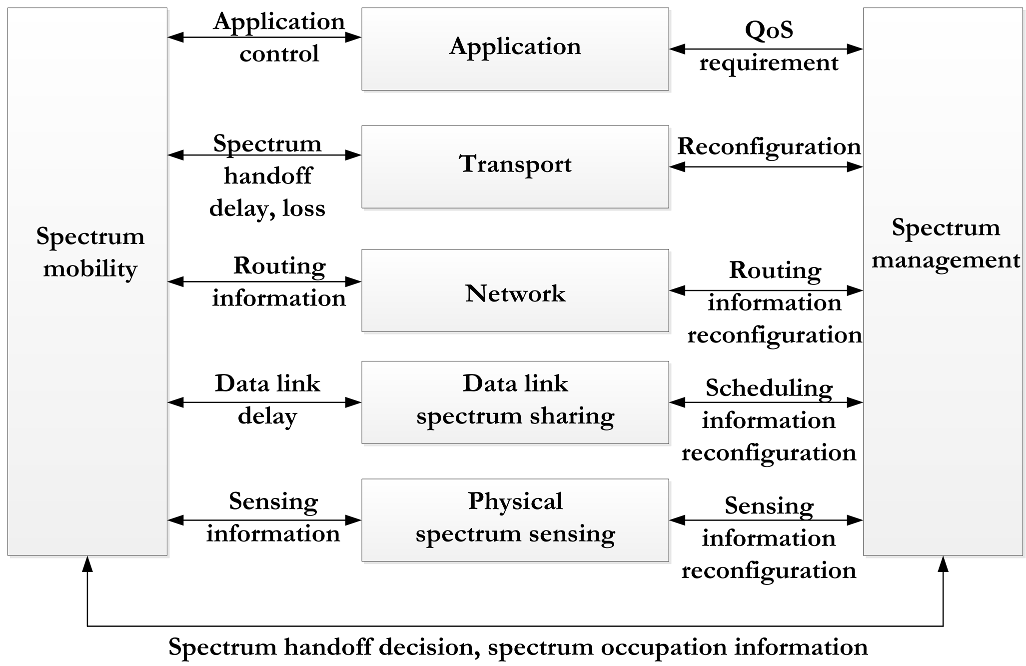

Fig. 1-3 Protocol stack for next generation cognitive radio networks

- Network layer: At the network layer, the selection of the transmission channel as described above, also determines the routing path. This is a key challenge as secondary CR nodes have limited local information, thus the unpredictable appearance of a primary users may disable certain channels, resulting on failures in the existing routes. In this case, the routing layer has two options. The first one prohibits the secondary operation in the affected region, thereby increasing the path length and, consequently, the End-to-End delay. The alternative permits the operation of secondary nodes in the affected region, however the exploited channel may be changed in the region of primary user (PU) activity keeping the routing path constant, thus incurring channel switching delay.
- Transport layer: As the transport protocol usually runs at the end nodes (source and destination), it only has a limited knowledge of the conditions of the intermediate nodes. Since typical routes in an ad hoc network may involve multiple hops, the End-to-End reliability becomes important. By regulating the transmission rate of the source, the transport layer adapts to the congestion in the route and maintains a buffer of unacknowledged packets for error recovery. The main problem in classical ad hoc networks is incorrectly attributing packet losses to network congestion, when they have been caused by the mobility of the nodes or by bad channel conditions. Several modifications are required to the transport layer protocols in order to consider the opportunistic availability of the spectrum resources.

In summary, CR networks are envisaged to solve the problem of spectrum scarcity by making efficient and opportunistic use of frequencies reserved for the use of licensed users of the bands (e.g. TVWS of the UHF/VHF band). To realize the goals of ubiquitous spectrum-aware communication, the CR networks need to incorporate a number of functionalities in the protocol stack as described above (i.e. the spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility). However, the main challenge is to integrate these functions in the layers of the protocol stack, so that the CR users can communicate reliably over a heterogeneous environment, with or without infrastructure support. Through the above discussion, a number of challenges arise in each layer of the protocol stack. Many researchers are currently studying and developing communication protocols and technologies that enable the reliable operation of CR networks in spectrum opportunities. However, to ensure efficient spectrum-aware communication, more research is needed especially in spectrum sharing though spectrum management, as well as in spectrum mobility when the secondary CR node tries to obtain optimal routing paths.

1.3.2. **Cognitive Radio Network Architectures**

Cognitive radio networks can be classified as infrastructure-based or ad-hoc, according to their topology, or as single-hop or multi-hop according to the communication between a transmitter and a receiver [10]. For example, in a single-hop infrastructure-based CR architecture, communication between unlicensed users is achieved through a central controller (e.g. a base station [10]), which takes the responsibility of managing and coordinating secondary spectrum access (e.g. allocation of time, frequency band, and transmit power). On the other hand, in a multi-hop infrastructure-based CR architecture multiple base stations are utilised (i.e. relay nodes), enabling unlicensed users to exchange data even though they are not in the transmission range of each other (multi-hop communication) [10]. In an ad-hoc CR architecture, the unlicensed users communicate with each other directly (i.e. in a peer-to-peer mode) without requiring any base station assistance. The communication can be either single-hop or multi-hop [10]. It should be noted that for multi-hop communications, some unlicensed users can temporarily assume the role of relay stations [36].

Moreover, CR networks can be based either on centralized architectures or distributed ones, depending on the place where the spectrum decision process takes place. Concerning the former, a central controller, (i.e. spectrum broker) makes the decision on spectrum access by collecting information about the spectrum usage of the licensed users as well as information about the transmission requirements of the unlicensed ones. Based on this information, an optimal dynamic spectrum access solution (e.g. one which maximizes spectrum utilisation) can be obtained. The decisions of the central controller are communicated/broadcasted to all the unlicensed users in the network. However, information collection and exchange to/from the central controller can incur a considerable overhead. On the other hand, in the case of distributed decision process for dynamic radio-resource exploitation, an unlicensed/secondary user can individually and autonomously decide on spectrum access. Since each unlicensed user has to collect information about the ambient radio environment and make its decision locally, the cognitive radio transceiver of each unlicensed user requires more computational resources than those required in centralized architectures. Even though, the communication overhead in this case would be smaller, since each user has only local information the optimal solution for spectrum access may not be achievable by all the unlicensed users. As shown in Fig. 1-4, distributed architectures can be implemented in both infrastructure-based and ad-hoc cognitive radio networks. Nevertheless, a centralized dynamic spectrum access can only be applied in an infrastructure-based network since it requires a central controller to plan, schedule, and optimize spectrum access by the unlicensed users. In the case of a multi-hop infrastructure-based network, one of the relay stations can assume the responsibility of controlling the dynamic spectrum access.

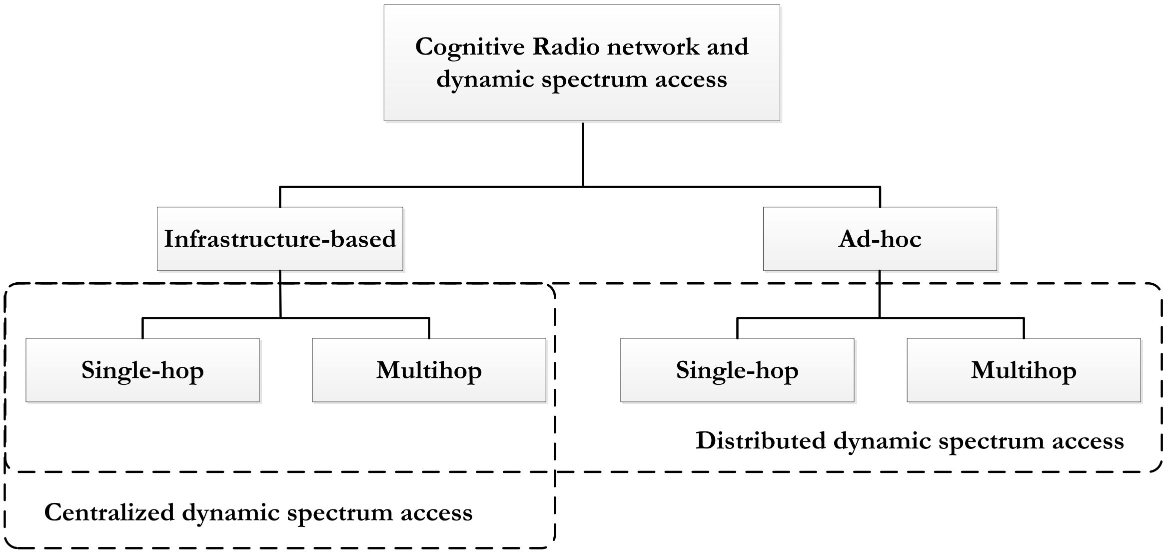

Fig. 1-4 Cognitive Radio Network Architectures Classification

1.4. Radio Spectrum Management Policies – Regulation Models

In all cases, and no matter which architecture is utilised, the introduction of CR networks in TVWS is hampered by the current "command-and-control" paradigm of TV/UHF spectrum management, that permits only licensed systems/users, such as DVB-T, DVB-H, iTV, etc., to the exploit radio spectrum, while it prohibits any other opportunistically unlicensed transmission. As a result, the spectrum remains under-utilized in many geographical locations. On the other hand, radio spectrum exploitation can be improved, if secondary (i.e. unlicensed) users are allowed to opportunistically access parts of it (e.g. TVWS), as long as their transmissions do not interrupt or interfere with transmissions from primary users (e.g. DVB-T, DVB-H). Thus, there is a universal recognition that the current regulatory model is not optimal and new spectrum models have to be adopted, in order to permit the exploitation of the radio spectrum to licensed systems as well as to unlicensed ones. Such regulation models are:

- The **Spectrum of Commons** representing an extreme point of view, in which the relationship with DVB-T is assured by controlling the levels of interference. This model promotes spectrum efficiency without QoS guarantees. The Spectrum of Commons is well-suited for optimum radio spectrum exploitation in cases of ad-hoc network architectures.
- The **Real-Time Secondary Spectrum Market** (RTSSM)which involves the sale of spectrum for applications that require sporadic access, establishing a secondary market for the lease and auction of spectrum. RTSSM is appropriate for centralized network architectures where a spectrum broker administrates the allocation of radio spectrum.

In this doctoral thesis a new approach is considered, where secondary users exploit TVWS (see Fig. 1-5), while it moves away from the binary choice of optimizing the current spectrum or buying new spectrum with exclusive rights.

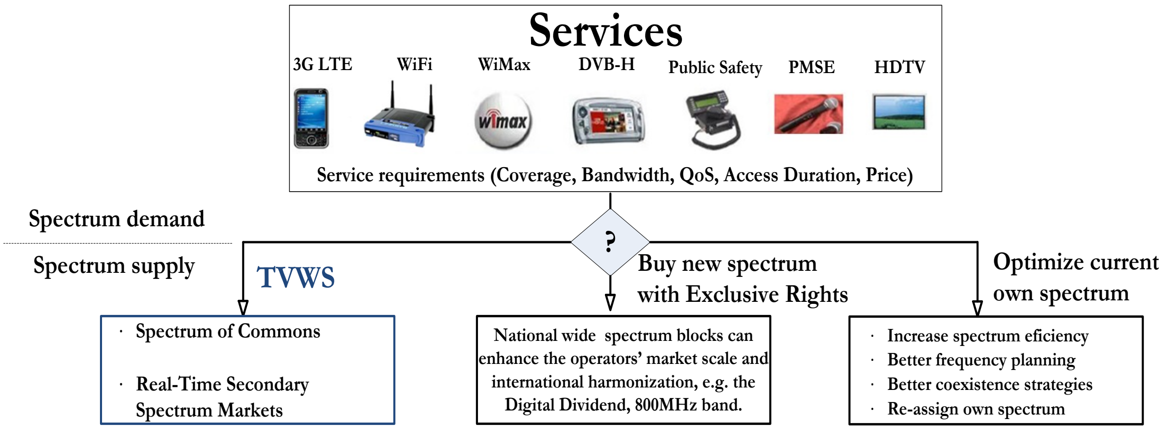

Fig. 1-5 TVWS trading model

In more detail, when extra spectrum is required to support a specific service with multidimensional requirements (including coverage, bandwidth, QoS, access duration, price), the operator has several options:

- **Optimize its current own spectrum allocation** for the efficient use of resources, which may be achieved in the way of better frequency planning, of creating better coexistence strategies or of re-assigning its own spectrum. This option is not always possible since the current wireless networks are usually spectrally efficient;
- **Buy new spectrum with exclusive rights**, e.g., the new released TV spectrum (790-862 MHz). If the operator wishes a nationwide development dimension for economies of scale and international harmonization is more likely to buy new spectrum with exclusive rights, e.g., the cleared spectrum that will be released after ASO (790-862 MHz). However, this solution may be costly for new entrants;
- **Novel TVWS approach**: obtain exclusive rights temporarily in the secondary market or new unlicensed bands within TVWS.

The TVWS approach is an attractive alternative where secondary spectrum markets help to promote efficient allocation, assignment and use of spectrum. They offer opportunities for licenced holders to trade licences or lease spectrum when demand and supply conditions change. As a result of changes in technology, business strategy and/or market share some licensees may hold spectrum they no longer need. They can sell or lease their surplus spectrum to secondary users, including other licensees who desire access to that spectrum. Secondary markets also allow the emergence of intermediaries that may trade in spectrum or lease it to third parties. In case of TVWS, these spectrum bands on a specific area are simply wasted, if they are not used by the secondary users either as spectrum commons or as through temporal licences obtained on the secondary spectrum market.

Spectrum trading and liberalisation will benefit spectrum users of various types [52]:

- Large users of spectrum, such as telecommunications companies, will benefit from a greater certainty over the term of their rights to use spectrum and the potential to access more spectrum for expanding technologies;
- Small users of spectrum, such as private business radio users, will benefit from the opportunity to profit from investing in new equipment and selling any spectrum that is released as a result, or to purchase more spectrum to expand their business;

- New entrants will have more opportunities to compete for spectrum for new technologies or services with incumbents. Spectrum trading and opportunities to change the use of spectrum will also remove barriers to entry in markets where the lack of access to spectrum previously restricted entry by new players.

Another notable benefit of spectrum trading is that it enhances the prospect of greater wireless deployment in underserved areas, e.g. in rural areas. Spectrum trading can thus help to provide the flexibility needed for the development of additional and innovative services in rural areas. However, there is concern that the spectrum trading activity may remain low in rural areas where there is a scarcity of frequencies, compared with the existing demand [52].

1.5. Data-link layer issues and the RRM process in CRNs

Vital parts of CR networks based on the RTSSM policy are the radio resource management (RRM), and the radio spectrum trading, both of which are data-link layer processes. While the former is considered as an optimized solution for allocating network resources in order to increase network performance, the latter takes into account economic issues and transactions of radio spectrum leasing, by considering a price per unit of spectrum (e.g. cost per MHz). In such cases, the optimization can be focus on optimizing either a single objective or a set of objectives; however, the nature of the wireless communications almost exclusively requires the multi-objective approach. The optimization in the cognitive radio paradigm formulates CR networking problems as optimization problems from the perspective of resource allocation and trading, towards maximizing or minimizing an objective function considering a number of constraints and restrictions that have to be satisfied. Usually, multi-objective optimization can be executed following either the decision making theory concept or the game theory concept. Whereas the former attempts to reach an optimal solution through classical mathematical rationalization, the latter models the optimization problem as conflicts and/or cooperation among competitive players.

1.5.1. Decision Making Spectrum Allocation

The decision making approach is based on formulating an objective function, as well as on setting equality and inequality constraints that the optimal solution must satisfy [10]. Three groups of solutions arise for this type of optimization approach, i.e. closed form solutions, mathematical programming and integer/combinatorial programming. The former is the general decision-making optimization understanding, where an optimization goal is reached by using approximations and solving Lagrangian equations in closed form.

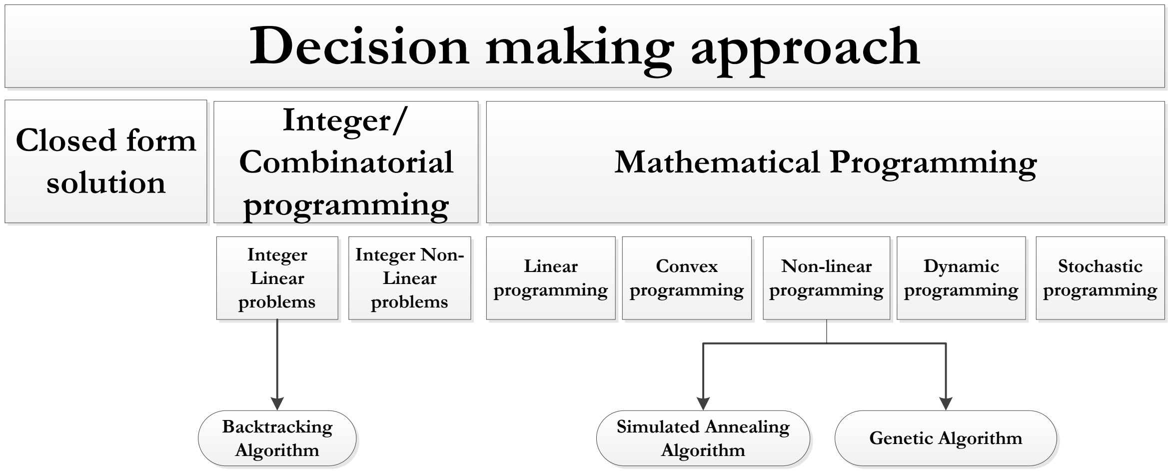

Fig. 1-6 Decision making Classification of Radio Spectrum Allocation Solutions

Mathematical programming is used for most real-world optimization problems it can be divided into 5 major subfields, i.e. linear, convex, non-linear, dynamic and stochastic. In linear programming a linear function is maximized/minimized over a convex polyhedron; the simplex method [37]. Convex programming is based on the convergence of the considered values towards the highest/lowest local value, by exploring the equality of the local and global optima. The optimization process involving non-linear objective functions and constraints is called non-linear programming. The key difference with linear programming is the inequality between the local optima and the global optimum i.e. there can be more global optima in which case a simple "climbing uphill" algorithm cannot solve the optimization problem. Popular solutions for solving a non-linear programming problem are genetic algorithms, simulated annealing and the Monte Carlo method. Dynamic programming is based on the optimality principle that states: "in an optimal sequence of decisions or choices, each subsequence must also be optimal". Two approaches can be considered, i.e. a top‑down approach, where the general problem is broken into sub-problems being optimized in order to reach an optimum for the general problem, and a bottom – up approach, where all sub-problems are envisioned in advance and larger problems are built up from their optimal solutions. The last subfield of mathematical programming is the stochastic programming, which is an optimization process that incorporates probabilistic elements in the problem formulation. Solution methodologies include a sampling method based on the Monte Carlo method, genetic algorithms and simulated annealing.

In addition, the integer/combinatorial programming (that belongs to decision making theory) encompasses the optimization problems that involve parameters with integer values or parameters that are of combinatorial nature (the word combinatorial refers to the fact that only a finite number of feasible alternative solutions exists). These are multi-objective problems that can be solved only through a search for the optimal answer through the entire set of possible answers. The goal of the integer/combinatorial programming is to shorten the search to a smaller subset of possibilities. In CR networks, integer/combinatorial optimization problem formulations can be used to obtain efficient resource allocation methods, which meet the desired objectives when the values of some or all of the decision variables are restricted to be integers. Constraints on basic resources, such as modulation, channel allocation, and coding rate, restrict the possible alternatives that are considered. For example, channel allocation, modulation level, channel coding rate, and even power take discrete values in a practical system.

1.5.2. Game Theory Spectrum Allocation

Moreover, an interesting research field in CR networks is resource allocation and trading from a game theoretic point of view. More specifically in several cases, secondary systems that dynamically and intelligently adapt their transmission characteristics do not have incentives to collaborate and thus they behave selfishly. A game theoretic perspective investigates this behaviour and provides solutions to wireless networking resource sharing, which is described as a multi-objective optimization problem. The spectrum sharing issue can be modelled as a game between primary and secondary systems with incentives to cooperate or not. Based on this approach, game theory is capable to provide comprehensive and straightforward equilibrium criteria, in order to evaluate game optimality, under various game settings.

Extensive and comprehensive research approaches have also been anticipated, according to economic interactions or decision-making in CR networks. Fig. 1-7 presents the classification of solutions in the radio spectrum allocation and trading problem.

Fig. 1-7 Economic-oriented Classification of Radio Spectrum Allocation Solutions

Radio spectrum management issues seen by economic perspective can be modelled/solved following either a) cooperative game theory, b) non-cooperative, c) price theory or d) market theory concepts. In a cooperative game, all participants collaborate, by acting as a distinct entity in order to maximize the overall utility. For instance, a bargain game is usually exploited, towards formulating an interaction between cooperative systems/players, considering that a system is possible to influence the actions of the other players. Moreover, participants in non-cooperative games behave selfishly, while individual players decide separately. In a non-cooperative environment, the player's incentives are usually competing. A non-cooperative game is usually exploited in order to reach an equilibrium solution, optimizing the payoff for all players. Such an example is the Nash equilibrium [38], where each player in the game cannot achieve an improved solution, if it deviates from the equilibrium.

Moreover, price theory has been exploited in order to determine the value of an item based on the player incentives. In the case of radio spectrum sharing, well-suited pricing schemes are important to determine the price per spectrum unit, by exploiting various economic models and by increasing the payoff for both primary and secondary players. Pricing is a vital issue towards to increasing the revenue of service providers, as well as towards protecting from unnecessary competition by optimally allocating radio spectrum resources. Furthermore, the market theory is an efficient method used for radio spectrum trading. More specifically, the market theory can be divided/grouped into Monopoly, Oligopoly and Competitive Equilibria [10]. The cooperative and non-cooperative games exploit game models, in order to analyse strategic interactions between players for wireless networking resources sharing. Such models are the Stackelberg game, the Bertrand game, the Cournot game, the Coalition game, the game with Learning, the Repeated game, the Bargaining game and the Modified Minority game [39]. Additionally, the price theory can be applied, by either exploiting Bargain theory or Auction theory. Bargain theory is an alternative strategy, mostly used in cases that price of resources is fixed. In such a case, both buyers and seller' come to an agreement after a conflict regarding the value of the resource. On the other hand, the auction theory [40] has been widely used for determining the optimal allocation of scarce resources that have an undetermined or variable price. Through an auction-based process, sellers aim to improve their revenue, by assigning the available radio spectrum to buyers who also increase their profit. Each player in auction theory sets a bid that reflects the player's value for the resources. A variety of auction-based processes can be exploited in radio spectrum allocation and trading challenges. The most widely exploited are single, double and combinatorial auction-based processes [10].

Bidders in a single auction set their bids and the auctioneer decides the winner of the process. The major types of single auctions include the English auction (i.e. increasing-price auction), the Vickrey auction (i.e. first-price sealed-bid and second-price sealed-bid auctions) and the Dutch auction (i.e. decreasing-price auction). Another set of auction-based processes includes the double auction. In this case, several radio spectrum players trade among them, heterogeneous or homogenous resources/items. Items can be auctioned at the same time (i.e. in a simultaneous auction) or sequentially (i.e. in a sequential auction) [41]. The last set of an auction-based process includes the combinatorial auction, where a single seller has multiple heterogeneous items for sale and bidders place their bids for parts of items on an "all-or-nothing" basis, (i.e. a bidder will pay for items only if it gets all of them). The most known combinatorial auction-based processes are the naive first-price auction [42] and the Vickerey-Clark-Grooves (VCG) auction [43].

Although the radio spectrum sharing problem may have a number of possible solutions, most of them have drawbacks in their applicability. For instance, several approaches based on the Nash equilibrium usually experience extreme competition between secondary and primary systems in non-cooperative games. This results some times to a situation where the solution of the game is not achieved or is inefficient. However, auction-based processes provide a solution methodology for radio spectrum sharing problems that fulfil the requirements of sellers, towards increasing their payoff, as well as the buyers' requirements to maintain their spectrum usage at the lowest possible cost.

The spectrum auction-based processes have been extensively exploited, in order to solve several types of wireless resource allocation problems. Sun et al. in [44], developed an auction-based algorithm that allows systems to fairly contend for fading channels. For this scope they utilize mechanisms based on a second-price auction process. Also, Wang et al. in [45], propose the cognitive radio network that is interference tolerant, where single primary systems share radio spectrum together with secondary systems with limited interference. Two common multi-unit auctions are presented in this research work. The first one is a Vickrey auction, while the second one is a sequential process of a first-price auction, towards assigning wireless resources and utilizing power allocation strategies for an optimum performance. Furthermore, [46] proposes two auction-based mechanisms, in order to share radio spectrum between a group of systems, considering several restrictions related with the interference temperature at measurement points, while [47] presents auction-based approaches (i.e. SNR and power auctions) to compute the relay selection, as well as the relay power allocation. The power auction achieves in this case an optimum resource allocation by increasing the total rate, while the SNR auction is more flexible regarding efficiency and fairness. Moreover, the approach proposed in [41] analyses the radio spectrum allocation problem under sequential and concurrent auctions, by considering a number of bidders that compete to access multiple parts of the radio spectrum. Furthermore, [48] considers the radio spectrum assignment as a double auction with multiple primary and secondary systems, proposing an approach based on dynamic pricing in order to optimize spectrum efficiency and maintain the incentives of the systems. On the other hand, an integrated assigning, billing and pricing system is considered in [49] for networking architectures based on the cognitive radio paradigm. A joint power/channel assigning scheme is proposed in [50] that is used to optimize network performance. In a general context, during an auction-based process for leasing radio spectrum resources, bidders propose their bids to the auctioneer, including information related with the price of bidding as well as the quantity per unit of spectrum. The auctioneer is then in charge to compute winning bidders and enable access to radio spectrum for them. Therefore, the radio spectrum is traded at a specific price defined according to the auction process. In such a case, the secondary systems state their needs, by sending their bids in order to obtain admission to wireless networking resources. An auction-based approach enables a number of secondary network operators to dynamically control the availability of radio spectrum, in contrast to research approaches based on fixed price markets where the networking systems are only permitted to inactively access resources under a first-come-first-served basis [51]. In this context and considering all the above mentioned state of the art research work, no related research approach has yet considered an auction-based process by simultaneously assigning TVWS during both the time and frequency domains.

1.6. Network Layer Issues in CRNs

A research challenge that has to be investigated in CR network architectures is related with the way that routing paths are established between CR nodes located in different areas. Routing is an important/core function in CR network architectures, since they enable the seamless connectivity of CR nodes as well the efficient data transfer between them. Routing in CR networks is also crucial for other design issues such as flow control and network mobility management. In this respect, this sub-chapter elaborates on a state-of-the-art on routing (e.g. conventional routing protocols) in ad-hoc and multi-hop networks since there they exhibit a strong similarity to CR networks. Conventional routing protocols are based on either link-state or distance vector algorithms aimed at identifying optimal routes to every node in multi-hop networks. Topological changes often encountered in the network are reflected through the propagation of periodic updates. To update and maintain routing consumes tremendous bandwidth and is not practical. For IP-based multi-hop networks, the routing protocols can be generally categorized as proactive or reactive, depending on whether the protocol continuously updates the routes or reacts on demand. Proactive protocols, also known as table-driven protocols, continuously determine the network connectivity and already-available routes to forward a packet. This kind of routing protocol is obviously infeasible in frequently re-configurable networks such as CR networks. Reactive protocols, also known as on-demand protocols, invoke the determination of routes only when it is needed (i.e., on-demand). Two well-known reactive protocols: are the Dynamic Source Routing (DSR) and the Ad-hoc on demand Distance Vector (AODV). When a route is needed, reactive protocols conduct some sort of global search such as flooding. They pay the price of delay to determine a route, but they obtain a picture of the most updated network topology (i.e., availability of links).

1.6.1. Routing protocols in conventional networks

In wireless networks two types of routing protocols can be utilized for reliable data delivery, the so called a) **proactive** (i.e. known as table driven) and b) the **reactive** (i.e. also called on-demand) protocols. The former are feasible when routes can be stored and maintained in routing tables, which means that nodes periodically register changes in the topology and update routing information. The latter can be utilized when routes are first discovered on demand, which is possible to happen when data need to be transmitted to a node where no route has yet been discovered. In the proactive approach the advantage is the small latency since routes are already available, while the disadvantage includes the increase of the routing traffic, since the routes require nodes to periodically update routing tables. On the opposite approach, the reactive protocols are capable to save bandwidth because it limits the routing overhead; however, they add latency at the beginning of the transmission to the nodes when no route has yet been discovered. Another crucial issue according to which the routing protocols can be categorized depends on the information that is stored in the packet header. Thus, the routing protocols can be separated in two categories, a) **source** and b) **hop-by-hop** protocols. The former include the entire route in the packet header while the latter include information about the destination in the header and use local tables to determine the next hop on the route. In source routing protocols, intermediate nodes are not required to update routing paths in order to forward packets, but the packet size can easily grow, especially in large networks. On the other hand, in hop-by-hop routing protocols the advantage is the small packet size, but the use of intermediate node's inevitable in order to maintain and exchange routing information.

As already mentioned above, the most widespread routing protocols for the conventional networks are the Ad-hoc On-demand Distance Vector (AODV) and the Dynamic Source Routing protocol (DSR). The former belongs to the reactive and hop-by-hop categories while the latter to the reactive and source categories. More specifically, AODV uses a route discovery process and makes hop-by-hop routing by broadcasting discovery packets only when necessary. AODV forwards information concerning changes in the local connectivity to neighbour nodes that are likely to need it. Also, AODV supports the exchange of routing messages (RREQ, RREP) between a source and a destination node. DSR consists of two mechanisms, the Route Discovery, which handles the establishment of routes and the Route Maintenance, which keeps route information updated. DSR operates on-demand in order to establish the data path, while it exchanges signalling information between source and destination nodes via RREQ (Route Request) and RREP (Rout Replay) messages.

1.6.2. Routing protocols in cognitive radio networks

A multi-hop Cognitive Radio network is, in many ways, similar to a multi-channel network. In both cases, each node has a set of channels available for communication. When two nodes wish to communicate, they negotiate the selection of a communicating channel. However, two are the major differences in such network environments. Firstly, in a multi-channel network, the number of channels available at each node is fixed and the channels have equal transmission ranges and bandwidths. On the other hand, in a multi-hop Cognitive Radio network the number of channels available at each node is variable and the environment is heterogeneous. Thus, it is possible that a secondary node does not have any available channel, due to the complete occupancy of the spectrum by primary systems.

This section presents the most recent proposed approaches been, regarding routing protocols which can be utilized in CR networks. More specifically, a routing protocol is proposed in

[63], that exploits the combination of geographical routing and radio spectrum assignment, towards avoiding regions with high presence of primary communication nodes. It also determines optimum routing path channel combinations that reduce delays in the network. A spectrum aware data adaptive routing algorithm is proposed in [64], where the end-to-end route selection depends on the amount of data to be transferred. Furthermore, the proposed routing protocol in [65] builds a forwarding mesh based on a set of available routes to the destination and opportunistically adapts during the forwarding process according to the dynamic radio spectrum conditions. A joint approach of on-demand routing and spectrum band selection is proposed in [66] for CR networking environments and a delay-based metric is used to evaluate the quality of the alternative routes. Most of these approaches utilize an AODV-style message for the route discovery and route reply. In the route discovery step, a RREQ (route request) message is sent by a source node to acquire the possible route to the destination. Also, the channel information (i.e. spectrum opportunities) is piggybacked with this RREQ message. Once the destination receives the RREQ message, it will have a full knowledge about the channel availability along the route from a source node. The destination then chooses the route with the lowest delay and assigns a channel to each node along the route. Then, the destination node sends back a RREP (route reply) message to the source. This message also contains the information on channel assignment so that the nodes along the route can adjust the channel allocation accordingly. Once a source node receives this RREP, it starts data transmission.

None of the above mentioned research approaches considers an heterogeneous environment, where secondary nodes cannot obtain a permanent common control channel, as the TVWS vary in time and space. Moreover, secondary nodes establish an ad-hoc mesh network, operating under the Spectrum of Commons policy [67], [68] that cannot guarantee QoS. As a result route maintenance is difficult to be obtained and consequently alternative paths need to be discovered.

1.7. Research challenges in Cognitive Radio Networks

1.7.1. Data-link layer Issues

The introduction of opportunistic cognitive radio networks in the licensed spectrum bands create new challenges in the current static resource management mechanisms/schemes that do not take advantage of frequency, time, geographic location and multiuser diversity. Thus, new radio resource management schemes are required in order to provide a better improvement, as well as to be able to adaptively assign system radio resources (frequency channels, power, and bit rate) as a function of traffic load, channel condition, channel information availability and QoS requirements. Several potential issues have to be considered in designing and implementing a radio resource management mechanism in a cognitive radio system, such as efficiency, applicability, QoS guarantees and fairness. However, radio resource management is not enough in order to satisfy all the above-mentioned requirements. Thus, a trading mechanism is essential in order to trade the resources by negotiating spectrum usage rights and spectrum pricing between primary and secondary users. Fairness is commonly exploited in order to assure a fair sharing of the system resources among the competitive secondary system. However, fairness depends to the scheme that is exploited by the network, such as the priority mechanisms and the billing mechanism. Otherwise the most straightforward kind of fairness concept is considered as the same allocation of the resources to all users. The problem arises in cases that the spectrum demand is higher than spectrum supply. In such cases, fairness mechanisms have to be implemented. On the other hand, QoS is a very challenging issue in opportunistic networks, in a high heterogeneous environment. Therefore, it is necessary that the radio resource management mechanism considers QoS explicitly, in the objective function, trying to maximize or minimize it. Fairness should still be considered but in conjunction with QoS. QoS can be taken into account by means of the user satisfaction ratio, which is the fraction of secondary user achieving their QoS targets in a given time period. Network efficiency/capacity, in turn, can be defined according to a minimum level of user satisfaction. Thus, a novel radio resource management mechanism has to be designed and implemented to address all the above-mentioned issues.

A vital challenge in dynamic spectrum access is to provide efficient radio spectrum utilization, satisfying most of the opportunistic networking devices and increasing profit of the spectrum seller (i.e. the spectrum broker). An optimal allocation of available resources (e.g. radio spectrum opportunities) in a CR network, can be achieved by considering the efficient co-operation between an RRM entity and a radio spectrum trading entity. The former efficiently assigns the available wireless networking resources (e.g. TVWS) as a function of the maxima possible utilization of them and the minimum spectrum fragmentation, by utilizing optimization approaches and methods [10]. Although several efforts [69], [70], [71], [72] addressed RRM challenges in CR networks, they mainly focus on resource management among primary and secondary systems, assuming an ideal spectrum sensing by secondary ones. However, an ideal spectrum sensing capabilities is impractical due to several issues, such as network connectivity, short sensing periods and hardware limitations [73]. Moreover, the on-going developments regarding the provision of multiple wireless networking services require the support of diverse QoS. Most existing research approaches elaborate on a single type of service provided by secondary systems. Moreover, RRM in a broker-based architecture that receives radio spectrum information from a Geo-location database with heterogeneous services with guaranteed QoS has been studied in [74], where the economic interaction among spectrum broker and secondary systems is also discussed.

In addition, the networking entity that is in charge of trading resources, undertakes economic issues and transactions of radio spectrum leasing, by considering a price per unit of spectrum (e.g. cost per MHz). The aim of this networking entity (e.g. spectrum broker) is to increase its profit during the spectrum assignment process, while secondary systems (e.g. spectrum buyers) wish to maximize the utility of the frequency resources usage and the satisfaction of QoS constraints. Such objectives are usually in conflict. A stable solution regarding radio spectrum assignment and pricing is required in order both the seller and the buyer fulfil their requirements. Pricing schemes are considered as a vital issue that is directly related to spectrum assignment, keeping fairness among secondary systems and offering profit to radio spectrum seller (e.g. spectrum broker).

1.7.2. **Network layer issues**

CR networks operating in heterogeneous TVWS cause new challenges in the design of communication protocols at the network layer as well. The key issues that have to be investigated when designing routing protocols for cognitive radio networks can be summarized below:

- The spectrum awareness issue has to be investigated, when studying routing in such an ad-hoc CR network, on secondary users are prohibited to operate in spectrum bands occupied by primary users. The goal of routing in such networks is to provide persistent high throughput communication by optimally selecting the appropriate path between secondary users. Thus, multi-hop connections must be set up between secondary user pairs with different spectrum availability and a new routing protocol has to be designed and adopted, to enable route discovery capabilities, taking into account spectrum heterogeneity in different geographical locations.

- Route quality issues [75] have also to be investigated, since the topology of such multi-hop CR networks is highly influenced by the primary users' behaviour, and classical ways of measuring/assessing the quality of end-to-end routes (nominal bandwidth, throughput, delay, energy efficiency and fairness) should be coupled with novel measures on path stability.
- Furthermore, route maintenance is a vital challenge due to the unpredictable appearance of a primary user at a specific time period that make a given channel unusable at the local level. This results most of the times resulting unpredictable route failures, which may require frequent path rerouting either in terms of nodes or in terms of used channels.

Routing in a TVWS based ad-hoc CR network constitutes a rather important but yet unexplored problem, especially when a multi-hop network architecture is considered. The design of a new routing protocol is therefore required to overcome the challenges defined above in order to establish and maintain optimal routing paths between secondary users with heterogeneous TVWS availabilities. Thus, the conventional routing protocols have to be modified accordingly in order to deal with these new challenges. For instance, a routing mechanism may require information exchange among the network nodes in order to select the best route. However, since in a cognitive radio network a common channel for this information exchange may not be available, the message broadcasting mechanism have to be enhanced/modified, in order to operate more efficient considering the dynamic spectrum access and the spectrum heterogeneity. Moreover, due to dramatically changes of network connectivity among primary and secondary nodes/users increase the demand of alternative routing paths. Thus, new routing metrics have to be defined, that should consider network parameters (e.g. hop-counts and link quality) as well as spectrum management parameters (e.g. interference to licensed users and the average number of available channels). For instance, Fig. 1-8 presents the case where a secondary node 1 wishes to communicate to secondary node 5 and there are two potential paths. The first path requires two hops, through node 3, while the second path requires three hops through nodes 2 and 4. However, the shortest route may cause interference to primary nodes, as the secondary node 3 operates close to licensed users. For this reason, the second flow can be used as an alternative in order to accommodate the flow. Last but not least, during periods that the primary users are inactive, the route through secondary user 3 can be utilized.

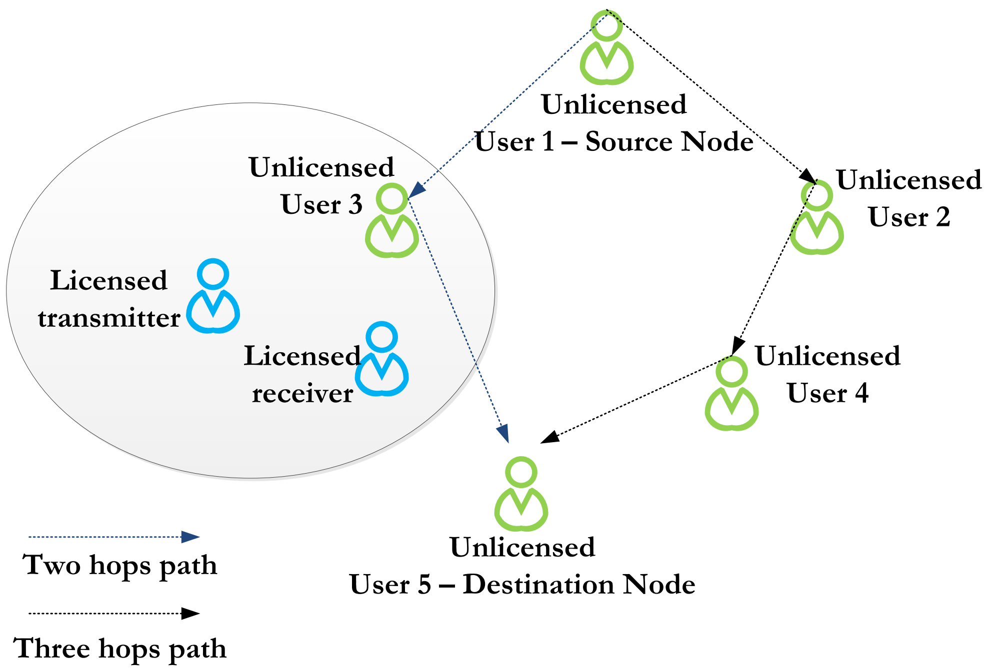

Fig. 1-8 Routing in the presence of licensed users

1.8. Summary

This chapter reviewed the state-of-the-art concerning TVWS and cognitive radio network principles, and provided a brief technology review of the existing approaches for optimum exploitation of these available radio resources. More specifically, it presented a promising technology of CR networks, capable to operate in TVWS, and presented architectures, configurations and potential policies that enable the TVWS exploitation by the CR networks. It also discussed the main principals and functionalities of CR networks that are based on the cognition cycle that includes attributes such as spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility, in order to obtain a choice/solution. In more detail, this chapter reviewed the most promising solutions for the realization of an efficient RRM and trading process. A categorization of decision making algorithms and game theory approaches are described since they may provide techniques in order to increase the network performance, as well as to administrate economic issues and other transactions of radio spectrum leasing. In both cases, a detailed state-of-the-art review was provided in order to mention the research work carried out until the present, as well as to focus on open research issues. Finally, this chapter elaborated on a number of technological challenges that are needed for the efficient exploitation of the available radio resources (i.e. RRM at the data-link layer), as well for the optimum communication and efficient data routing among secondary users (i.e. routing protocols at the network layer).

2. SYSTEM DESIGN OF A HYBRID COGNITIVE RADIO NETWORK ARCHITECTURE

2.1. Introduction

This chapter proposes a prototype hybrid system architecture and the corresponding data-link layer mechanisms. A centralized cognitive radio network is described, where the inter-system communication, in terms of dynamic TVWS allocation among various secondary systems, is coordinated by a spectrum broker following the Real-time Secondary Spectrum Markets (RTSSM) policy. The spectrum broker optimally administers the available resources interconnected with a Geo-location spectrum database, which is utilized to provide information for primary system protection. It also manages the economics of TVWS leasing either via fixed-price or via auction-based transactions. For efficient system performance, as a function of maximum possible radio resource exploitation and/or trading revenue, this chapter provides on the design and implementation of a prototype RRM and Trading framework at the spectrum broker side in order to optimally manage TVWS access. An RRM algorithm is designed, developed and incorporated in the proposed hybrid system architecture, enabling for efficient TVWS exploitation, providing QoS to secondary systems, minimizing spectrum fragmentation and maximizing spectrum broker profit. The proposed research approach considers an un-direct negotiation among primary and secondary systems, thus it incorporates a spectrum broker to trade the TVWS. This un-direct broker-based negotiation, minimizes the probability that the primary system becomes "selfish" overcharging the available radio spectrum, while it also guarantees QoS during TVWS allocation process.

2.2. Overall Network Architecture

This section elaborates on the description of the proposed hybrid CR network architecture, where TVWS administration among secondary systems is managed by a spectrum broker following the RTSSM policy for the inter-system communication. For this scope, a centralized topology approach was adopted as the most appropriate solution, since QoS guarantee is crucial in the proposed system. Furthermore, such a topology enables for radio spectrum trading, establishing secondary markets for spectrum leasing and spectrum auction. The spectrum broker entity in this network topology controls the amount of bandwidth and power assigned to each secondary user, in order to keep the desired QoS and interference below the regulatory limits. In this reference model, the centralized broker is an intermediary between the Geo-location database (TVWS information supplier) and players that negotiate spectrum on behalf of spectrum users. The inter-system operation of such a centralized infrastructure-based CR network, exploits RTSSM policy, where radio resource administration and spectrum leasing/auction is carried over a prototype RMM as depicted in Fig. 2-1. More specifically, this approach consists/comprises of two core subsystems: a) a Spectrum Broker responsible for coordinating TVWS access and administrating the economics of radio-spectrum exploitation, and b) a number of Secondary Systems or SS (i.e. mobile network operators and wireless network providers such as LTE, WiMax, UMTS, WiFi), each one accommodating users geographically adjacent to it, competing/requesting for TVWS utilization. In particular, this network architecture consists of secondary systems that provide different services classes depending on the type of service, voice data, etc. In addition, the intra-system operation of the proposed architecture follows the Spectrum of Commons policy, enabling for efficient ad-hoc communication among users/nodes located in areas with heterogeneous TVWS availability.

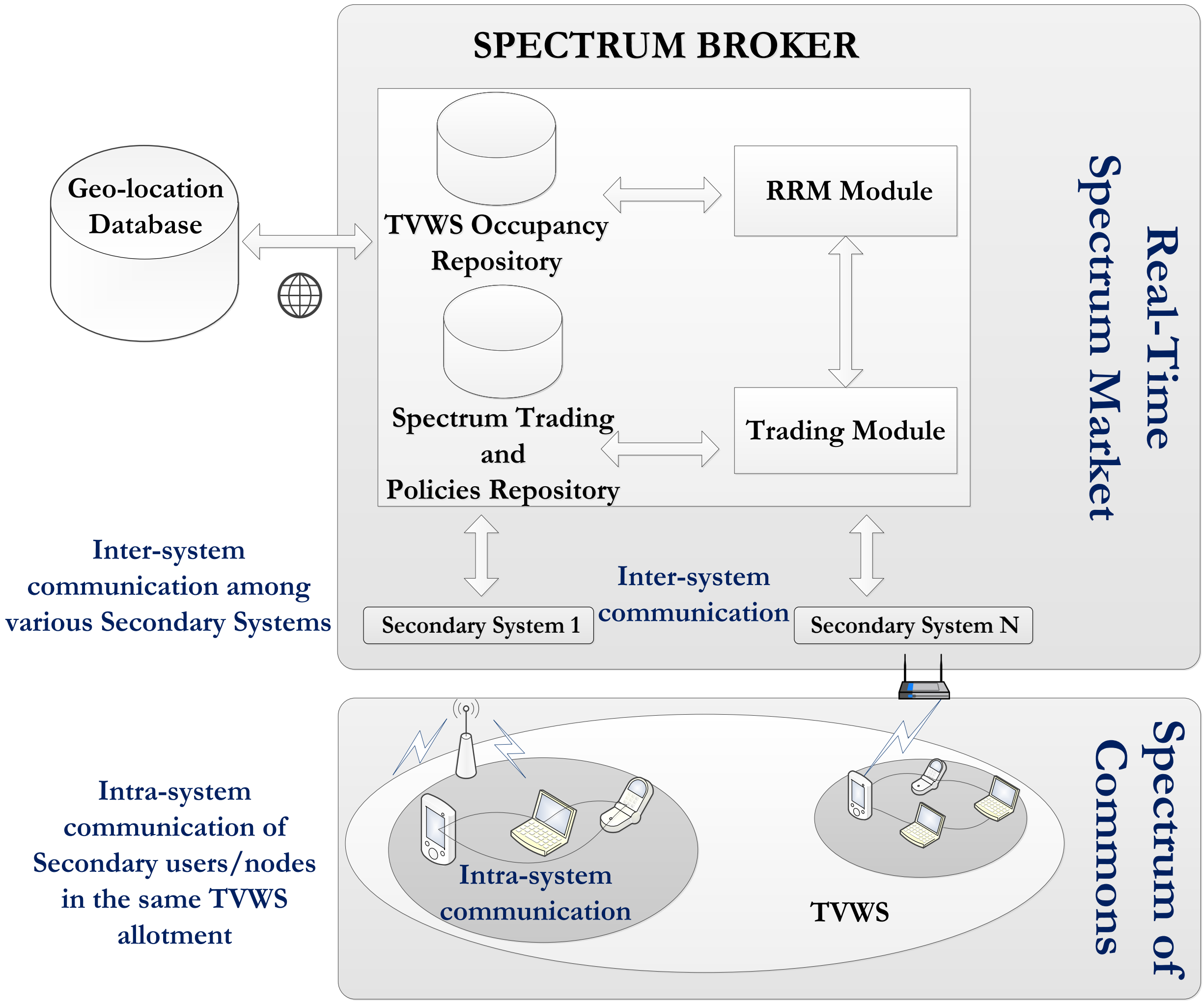

Fig. 2-1 Hybrid CR network architecture under the RTSSM and Spectrum of Commons policy

In particular, spectrum broker consists of two sub-entities, a Dynamic TVWS Allocation Mechanism (RRM module), as well as a Trading and Price Discovery mechanism (Trading module), and a number of repositories. TVWS occupancy repository obtains information from the national database, namely the Geo-location spectrum database (spectrum information supplier), which includes data, towards creating a pool of TVWS channels that are available in particular geographical locations. Furthermore, information regarding digital terrestrial television protected areas, protection rules and propagation models, are exploited to calculate maximum thresholds of operation transmission power of secondary systems, towards avoiding possible interference with primary systems. Geo-location database is possible to dynamically store new data and continuously change several parameters, regarding the protection of possible interference caused to primary systems. The Geo-location database frequently updates TVWS occupancy repository, in order the latter to create a spectrum-portfolio, including all the above-mentioned information that is advertised to all bidders. Moreover, the RRM module matches the secondary systems requirements with available resources and thus allocates TVWS based on QoS requirements. The TVWS allocation mechanism implements an algorithm that uses information from the Geo-location database to determine TVWS bands and power, at which a secondary system should be allowed to operate, in order to avoid spectrum fragmentation, optimize QoS and guarantee fairness in TVWS access. Moreover, trading module is responsible to determine the revenue of spectrum broker, which aims to trade/lease spectrum with temporary exclusive rights to the most valuable bidder. Finally, the trading information repository hosts information about TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading phase, creating a price-portfolio.

Secondary systems and devices have in principle two methods to determine if a channel is occupied or not. The first choice is to use sensing techniques, where channels are detected to find incumbent signals at or above certain signal strength. The second choice is to exploit a Geo-location database, where for a certain region attribution of channels to primary users is presented. More specifically, spectrum sensing has been widely exploited in cognitive radio systems, as a key functionality of them, incorporating power control mechanisms, able to dynamically adjust transmission power for efficient exploitation of spectrum opportunities (e.g. TVWS). The objective of sensing is to get reliable context information, in order to flexibly set the maximum transmission power per channel at the operating location to avoid causing interference to incumbent devices. Autonomous sensing techniques rely only on the power strength measured in specific CR locations. The decision whether a TV channel is occupied or idle is performed, by comparing the measured power strength with a threshold level. However, to avoid hidden-node problem, the channel must be sensed at very low levels of signal strength, e.g. -126 dBm for wireless microphones, which is less than the noise floor (-121 dBm). Sensing at this level may raise the false alarm rate.

On the other hand, the main purpose of the Geo-location database is to enable the protection of the incumbent systems from harmful interference (DVB-T and PMSE). Besides the information on the incumbent systems that a database holds, it may also include the Geo-location information per geographic pixel for a specific region and records of secondary systems that operate in a specific region. The structure of such a database is designed to accommodate data about incumbent systems. Furthermore, the database includes regulatory information, information from a central database, regarding border incumbent stations and a record of white space devices that access the database. An important part of the database is geographical data. Such data holds the terrain and building information available in order to calculate the available TVWS. The Geo-location database can greatly reduce the false alarm rate. However databases need to be updated with correct information as time goes by, otherwise errors will lead to interference in the field.

In this respect, a CR network may adopt a hybrid approach, where local sensing information is combined with Geo-location database information to compute the TVWS spectrum pool, in order to obtain optimum channel occupancy and minimise false alarm rate. Moreover, with a database, part of the complexity associated with sensing and maximum power computation is transferred to the core network, decreasing complexity and power demand of TVWS devices. The database has the ability to be dynamically updated and continuously adjust interference protection parameters in line with the evolution of incumbent standards, e.g. DVB-T2. In addition, TVWS spectral utilization efficiency is better than using sensing alone detection. This is primarily due to the ability of Geo-location enabled TVWS devices to accurately determine protected service contours.

More specifically, and according to this architecture, spectrum broker initially advertises related information, regarding TVWS portions, which are available for leasing and relevant data, regarding limitations of maximum tolerable transmission power per channel. Such data is derived from the Geo-location database and is maintained inside the TVWS occupancy repository. Secondary systems provide their requests through bids, to the spectrum broker (e.g. via dedicated links), indicating their interest related with specific units of radio spectrum and their offered price. Spectrum broker then gathers all relevant interests/bids and stores such data to Radio Resource Management module (RRM) module (Fig. 2-1) in order the latter to analyse and process the bids as a matter of the Secondary System technical requirements (e.g. requested BW, transmission power, etc.) and the locally available TVWS channel characteristics (hosted within the TVWS Occupancy Repository – see Fig. 2-1). Prior to any spectrum allocation, the economics of TVWS transactions are also analysed/elaborated (Trading Module in Fig. 2-1), taking into account the spectrum-unit price (e.g. cost per MHz) either based on fixed-price or spectrum-auction policies (Spectrum Trading Policies Repository in Fig. 2-1). Finally, an optimised solution combining the RRM results and the Trading Module output is obtained, enabling the Broker to sell/assign TVWS frequencies to the corresponding Secondary Systems under the Real Time Secondary Spectrum Market regime/policy.

In other words, all activities within the envisaged Real Time Secondary Spectrum Market are coordinated by the Broker, which is responsible for obtaining the best-matching solution through an optimisation-based process, taking into account parameters with integer values or combinatorial nature, such as the number of the available TVWS channels, the number of secondary systems, the required bandwidth, the maximum allowable transmitted power, the spectrum-unit price, etc. Eventually, the anticipated best-matching solution (spectrum allocation scheme) will be the result of two alternative TVWS allocation mechanisms, following either a fixed-price or an auction-based policy. In case that a fixed-price policy is adopted, an optimization algorithm (e.g. Backtracking, Pruning (2.4.1), Simulated Annealing (2.4.2), Genetic Algorithm (2.4.3)) obtains the best-matching/optimal solution, by minimizing an objective function, as a matter of spectrum fragmentation and/or Secondary Systems prioritization (e.g. in case that some secondary technologies must be served before others). Alternatively, in the auction-based policy, the spectrum broker collects bids from the secondary systems, and subsequently an optimization algorithm can determine the allocation solution along with the price for each spectrum portion from a price portfolio in order to maximize the spectrum broker profit. The auction process is then being repeated as soon as spectrum portions are available.

2.3. Spectrum Allocation Process

This section describes the spectrum allocation/leasing problem, by providing the problem formulation of both fixed-price and auction-based approaches. Spectrum broker is responsible in both cases to efficiently trade TVWS and allocate them to various bidders (i.e. secondary systems) that compete to each other, in order to obtain the available resources. According to initial measurements conducted in Munich area [76], [77] frequency availability comprises of ten TV channels (i.e. 8MHz each), scattered among digital terrestrial television radio spectrum. More specifically, Fig. 2-2 depicts vacant and occupied channels in UHF spectrum that includes four fragments, denoted as F, each one with different power and bandwidth requirements, denoted as Fi, where i represents the sequence number of the fragments. Based on such radio spectrum pool, fragments sizes are F1 = 24MHz (i.e. three UHF channels "40, 41, 42" of 8MHz each one), F2 = 8MHz (i.e. one UHF channel "46"), F3=24MHz (i.e. three UHF channels "50, 51, 53") and F4 = 24MHz, (i.e. three UHF channels 58, 59, 60), while aggregated available radio spectrum is 80 MHz. Fig. 2-2 also represents spectrum availability considering frequency and time domains, denoted as Δt and Δf interval, while for each (Δt, Δf) an unused part of radio spectrum is available for a specific duration/time slot.

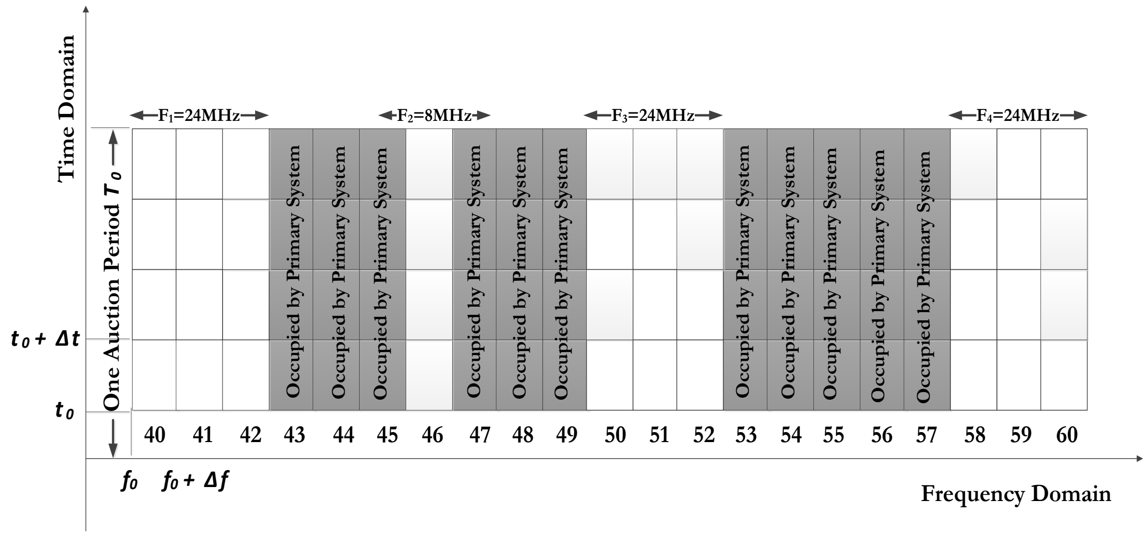

Fig. 2-2 TVWS allocation time and frequency domains TVWS in "time – frequency" domains and number of fragments based on availability in Munich area

Next sub-sections elaborate to describe the proposed RRM and trading modules, operating in spectrum broker in order to optimally allocate/lease the available TVWS, considering the two basic approaches, based on fixed-price and auction theory. The allocation mechanism has three major procedures: I. Preparation and Analysis, II. Operation and III. Maintenance.

2.3.1. **Preparation and Analysis phase**

During the Preparation and Analysis phase, the RRM establishes all possible solutions for allocating the available TVWS to competing SS and creates a spectrum portfolio comprising only valid solutions, i.e. those allocation schemes that match the SS technical requirements/specifications with the TVWS characteristics (valid solutions). In other words, this spectrum portfolio is the set ("A'_n") of valid allocation solutions, when an optimisation-based approach is applied over all possible combinations. For example, assuming that "F" is the total available TVWS channels and "V" the number of all competing secondary systems, it comes (by applying Equation 2-1) that the number of all possible combinations/solutions (NPS) will be:

$$NPS = \frac{F!}{(F-V)!} + \sum_{x=1}^{V-1} (F * V * x)$$

Equation 2-1

each one denoting a specific allocation scheme/pattern for assigning a certain TVWS frequency to a single SS. From all these solutions, the spectrum portfolio will include only those matching the SS technical specifications, such as the maximum allowable power $P(i,f)$ and the transmission bandwidth $BW(i,f)$, thus constituting a subset of NPS solutions when a an optimisation approach is applied over them (i.e. over all NPS solutions) following the objective function $C(\mathrm{A'}_{\mathrm{n}})$:

$$C(\mathrm{A'}_{\mathrm{n}}) = \sum_{i \in V} \sum_{f \in F} x_{if} P(i,f) BW(i,f)$$

Equation 2-2

where n = {1…NPS}, and x_{if} is equal to one, when the TVWS "f" is allocated to the SS "i", while x_{if} is equal to zero in other situation.

Also,

$$P(i,f) = \sum_{f \in F} p\,(f) x_{if}$$

Equation 2-3

denoting the allocation x_{if} where the maximum allowed power of the "f" TVWS can satisfy the SS technical requirements.

Also

$$BW(i,f) = \sum_{i \in V} b\,(i) x_{if}$$

Equation 2-4

represents the bandwidth of the allocation x_{if} where the "i" Secondary System can be satisfied from the "f" TVWS.

The logical diagram for RRM module is depicted in Fig. 2-3, where the first step is the process/calculation of all possible TVWS allocation schemes, as a matter of the number of competing secondary systems ("V") and the number of the available TVWS channels ("F") hosted by the TVWS Occupancy Repository. Following Fig. 2-3, this "Process Data" function is an iterative process with "NPS" stages (Equation 2-1), and therefore "NPS" combinations, which constitute the "Possible Allocation Solutions". As soon as all these Possible Allocation Solutions/combinations are established (A_n), the optimization algorithm (i.e. Backtracking, Pruning, Simulating Annealing, Genetic Algorithm) calculates/finds the optimum ones, which match specific technical requirements of the competing secondary systems (e.g. power level constraint, BW, etc.) with the available TVWS characteristics. These optimised Allocation Solutions (A'_n), i.e. a subset of (A_n), comprise the Spectrum Portfolio that will be used by the spectrum broker during the Trading phase. More specifically, and according to Fig. 2-3, this Spectrum Portfolio is the result of the iterative process "IsValidSolution", which examines if a Possible Allocation Solution/Scheme fulfils the technical requirements. In such a case, the Possible Allocation Solution is registered in the spectrum portfolio, otherwise it is discarded.

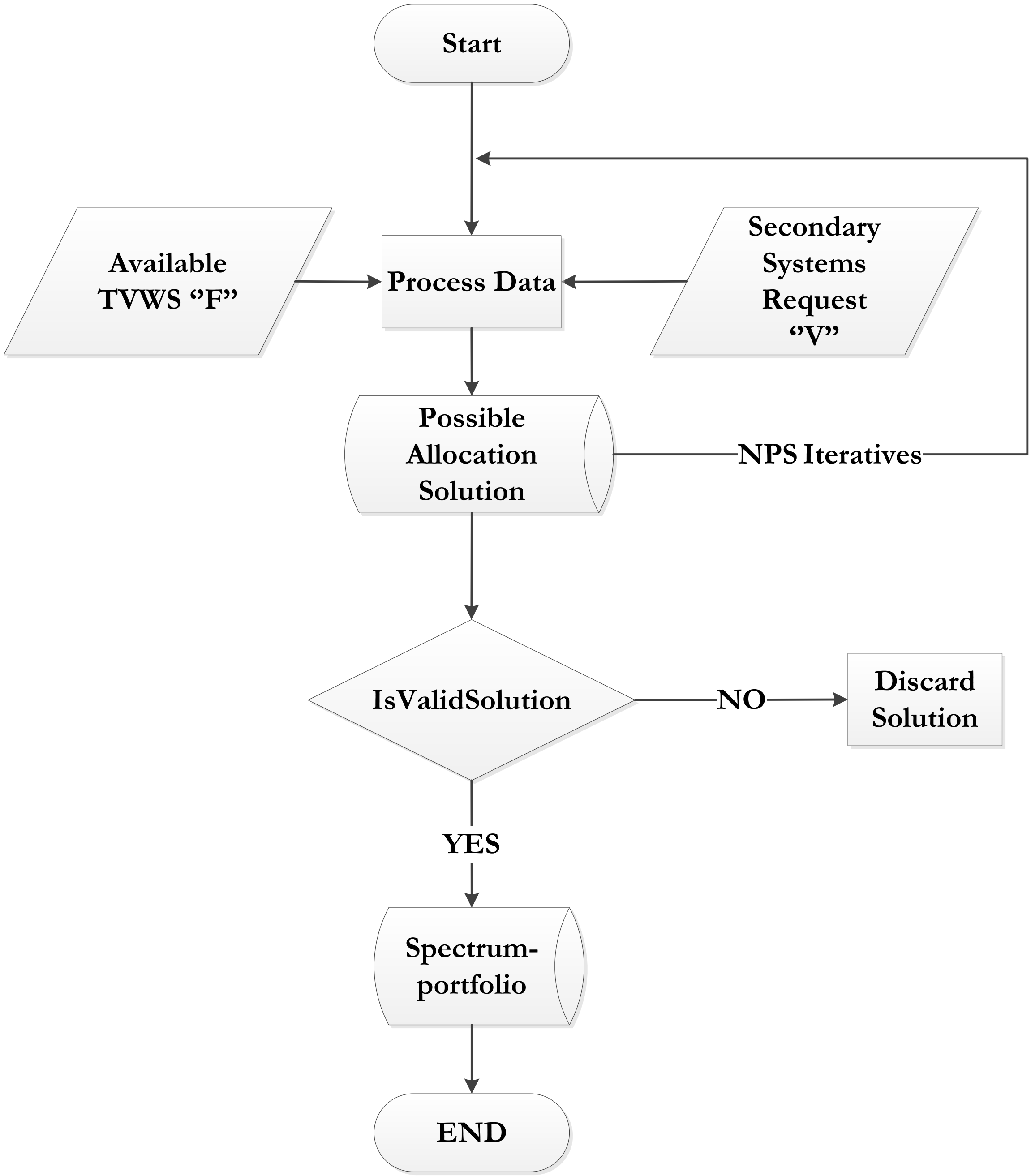

Fig. 2-3 Logical Diagram of RRM for the creation of spectrum-portfolio

2.3.2. **Trading phase**

During this phase, Trading Module within the Broker elaborates on the economics of TVWS transactions and decides upon the best-matching solution, following specific trading policies under the RTSSM policy. More specifically, Trading Module estimates the cost of every TVWS Allocation Scheme (present within the spectrum portfolio), taking into account a "spectrum-unit price" (e.g. cost per MHz) either under a fixed-value or an auction-based trading policy. For this reason, a Price-Portfolio is created/maintained within the spectrum broker (see Spectrum Trading and Policy Repository in Fig. 2-1), based on various price estimation methods [78], [79], among which are the Market Valuation ones (e.g. Spectrum

Market Transaction, Value of Spectrum Owning Companies, Capacity Sales of Spectrum-Utilising services, etc. – [78], [79]) and the Direct Calculation methods, including the Standard Net Present Value (NPV) and Least Cost Alternative (LCA) [78], [79]. In turn, and according to the logical diagram in Fig. 2-4, the selection of the best-matching solution (Optimal Solution) is the result of an optimisation process (utilising Backtracking, Pruning, Simulated Annealing or Genetic algorithm) targeting either to minimise spectrum fragmentation (fixed-price policy) or to maximise the profit (auction-based trading).

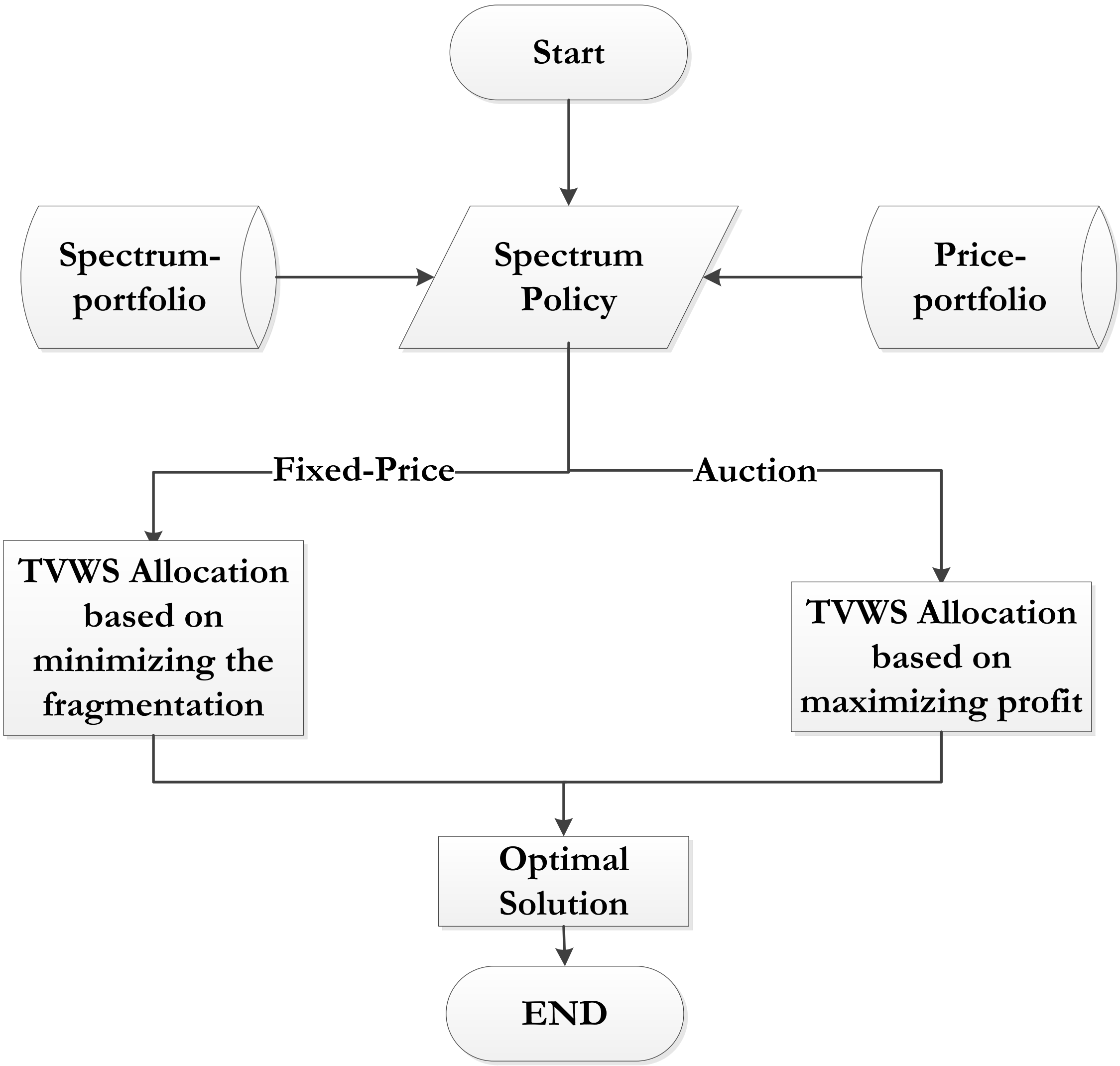

Fig. 2-4 Logical diagram of trading phase

2.3.2.1. Fixed-price Trading

If a fixed-price policy is selected (see fixed-price algorithm in Table 1), the spectrum allocation algorithm obtains the best-matching solution (Optimal Solution) by minimising an objective function "C(A')" (i.e. Equation 2-5, Equation 2-6), as a matter of allowable transmission power $P(i,f)$, requested bandwidth $BW(i,f)$, spectrum fragmentation $Frag(i,f)$, when a secondary system "i" is assigned to a specific frequency "f" and/or secondary systems prioritisation $\Pr(i)$ (e.g. in case that a number of secondary systems must be served before other ones, due to higher QoS level priority).

$$\boldsymbol{min}: \boldsymbol{C}(\boldsymbol{A}') = \boldsymbol{C}(\boldsymbol{A}'_{\boldsymbol{n}}) \sum_{\boldsymbol{i}\in \boldsymbol{V}} \sum_{\boldsymbol{f}\in \boldsymbol{F}} \boldsymbol{Frag}(\boldsymbol{i},\boldsymbol{f})\, \mathbf{Pr}\,(\boldsymbol{i})$$

Equation 2-5

or

$$\boldsymbol{min}: \boldsymbol{C}(\boldsymbol{A}') = \sum_{\boldsymbol{i}\in \boldsymbol{V}} \sum_{\boldsymbol{f}\in \boldsymbol{F}} \boldsymbol{x_{if}} \boldsymbol{P}(\boldsymbol{i},\boldsymbol{f})\boldsymbol{BW}(\boldsymbol{i},\boldsymbol{f})\, \boldsymbol{Frag}(\boldsymbol{i},\boldsymbol{f})\mathbf{Pr}\,(\boldsymbol{i})$$

Equation 2-6

where $Frag(i,f)$ denotes the spectrum fragmentation level (as a percentage) when a secondary system "i" is assigned to a specific frequency "f".

$$Frag(i,f) = \sum_{f\in F} frg\,(f) x_{if}$$

Equation 2-7

Inputs: TVWSpool, Location(x,y), Powermax, DemandSS
Update TVWS repository from Geo-location database
Estimate the spectrum-unit price
Create and advertise price-portfolio
Receive secondary systems request R= $\{R_1,\ldots, R_I\}$, where $R_i = \{x_i, t_i\}$
for all Requests **do**
    Sort R_i in descending order based on priority and update the price-portfolio
end for
Calculate the minimum fragmentation (Frag(i,f)) for all secondary system requests
Create initial solution S
for i = 1 to subset of variable length **do**
    Generate a new solution S_i
        if (Objective_function(S) ≤ Objective_function(S_i))
            then save the new allocation solution S_i to best found S
        end if
end for
return Best Allocation Solution

Table 1 Fixed-Price Algorithm Pseudo-Code

2.3.2.2. **Auction-based Trading**

Alternatively, auction-based process is best suited in cases that total requirement for radio spectrum is considered more than the available radio resources (i.e. Equation 2-8).

$$\sum_{i=1}^{i} s_i > S$$

Equation 2-8

According to the auction-based process (i.e. auction-based algorithm in Table 2), spectrum broker determines the optimal allocation solution, considering the maximization of its own income. To occur this, spectrum broker undertakes the trading mechanism that collects bids to buy from the secondary systems, bids to sell from the Spectrum Trading and Policies Repository, and subsequently determines the allocation solution along with the price for each spectrum portion from the price portfolio in order to maximize the spectrum broker profit. The auction would then be repeated as spectrum portions become available (i.e. as they are released by supplying players).

Furthermore, when the auction-based algorithm is followed, radio spectrum sellers are denoted as N = {1,2,…,n}. N is 1 in the proposed CR networking architecture, according to the simulation scenario (i.e. Spectrum broker, leasing the available TVWS S = {1,2,…,s} to I = {1,2,…,i} secondary systems). Each buyer "i" is able to purchase x_i portions of radio spectrum for a specific time period t_i, by reporting a price $P_i^{(b)} = \{x_i, t_i\}$ (i.e. Bid Price of m for specific portion of spectrum in a specific time), while spectrum broker leases y_n portions of radio spectrum for a specific time t_i, by reporting a price $P_n^{(s)} = \{y_n, t_i\}$ (i.e. Asking Price of m for specific portion of spectrum in a specific time). Finally, $x_{i,n}$ is the quantity, which is leased by "i" secondary system from spectrum broker. The pair (i,s) in the pseudo-code of Table 2 represents possible combinations of solutions, regarding "s" TVWS to "i" Secondary systems. In case that spectrum broker benefit has to be maximized, an optimization problem is formulated as follows, based on linear programming (i.e. Equation 2-9):

$$max: \sum_{i=1}^{i} \sum_{n=1}^{n} x_{i,n} t_i \left(P_i^{(b)} - P_n^{(s)}\right)$$

Equation 2-9

1: **Inputs**: TVWSpool, Location(x,y), Powermax, DemandSS
2: Update TVWS repository from Geo-location database
3: Estimate the spectrum-unit price
4: Create and advertise price-portfolio
5: Receive secondary systems bids P(b) = {P1(b),…, PI(b)}, where Pi(b) = {xi, ti}
6: **for** all Bids **do**
7: Sort Pi(b) in descending order based on price and create the auction-portfolio
8: **end for**
9: Calculate the highest valuation S[i,s] for all TVWS slots (i,s) ∍ {1, 2,…, m}

```
set Soptimal = S[i,s] //Random solution for algorithm initiation
for slot =1 to m do //Iteration process in order to find the best solution
    if (S[i,s]) ≤ (S[i+1, s+1]) // Check if the current solution is better or not to the
                                   neighbour solution
        then save the new allocation solution (S[i+1, s+1]) to the best found
    end if
end for
return Best Solution
```

Table 2 Auction-Based Algorithm Pseudo-Code

2.3.3. Maintenance phase

Phase III, Maintenance, involves the Update of TVWS occupancy repository for recently allocated spectrum with the coverage area of the secondary systems. The algorithm can be run again, when there is still an unused spectrum and a demand from new incoming secondary users or in a periodic basis (the market opens every day or every week).

2.4. Optimization Algorithms for TVWS Allocation/Leasing

A vital part in the proposed centralised CR network architecture is the radio resource management entity (RRM), which is responsible for the radio resource allocation/leasing process, besides satisfying the Secondary Systems QoS requirements and maintaining interference-free operation among Primary and Secondary Systems. To achieve these, the RRM exploits optimization methods [10], [14], among which are the decision-making ones that are trying to reach an optimal solution through classical mathematical rationalization, i.e. by formulating an objective function so that equality and inequality constraints are not crossed [14]. Such decision-making RRMs may be implemented, through a number of optimisation techniques, such as the integer/combinatorial programming (e.g. Backtracking) and the mathematical programming (e.g. Simulated Annealing). While the former provides a "global" optimum solution among all possible ones, the latter picks it from a smaller set of solutions that satisfy the objective function [37]. It should be noted, however, that the choice of the most appropriate decision-making RRM implementation technique constitutes an application-driven approach, based on specific use-case scenarios, and by taking into account the corresponding implementation intricacies. Thereupon, metrics such as the complexity of the RRM algorithm, the range of the possible solutions to be checked, the processing time and computational power required for obtaining the optimum solution have to be considered prior to choosing the most applicable technique.

2.4.1. Backtracking Algorithm and Pruning

The simplest approach in order to solve an integer-programming problem, such as spectrum allocation in CR networks, is to generate all possible spectrum allocations, by performing systematic/exact search. Backtracking [37], is capable to generate each one possible spectrum allocation solution exactly once avoiding both repetitions and missing solutions. Backtracking generates all possible solutions based on the available resources and the SS request by repeatedly choosing a SS request to accommodate in an available channel. In the backtracking method, as soon as an allocation solution is generated, the validity of the constraint is checked. If an allocation solution violates any of the constraints, backtracking reject this one, thus is able to eliminate a subspace of all variable domains. The backtracking algorithm may be improved by some filtering techniques, which aim at pruning the search space in order to decrease the overall duration of the search. The pseudocode of Backtracking algorithm is presented in Table 3.

Backtracking()

1: Create initial solution S

2: **for** i = 1 to subset of variable length **do**

3: Generate a new solution S_i

4: **if** (Objective_function(S) ≤ Objective_function(S_i))

5: **then** save the new solution S_i to best found S

6: **else** reject the S_i solution

7: **Return** S

Table 3 Backtracking Algorithm pseudo-code

2.4.2. Simulated Annealing

On the other hand, Simulated Annealing (SA) [37] is a heuristic algorithm for the global optimisation problem, which can be applied in resource allocation. SA algorithm replaces, at each step, the current allocation solution by a random "nearby" solution. This allocation solution is chosen with a probability that depends on the difference between the corresponding function values and on a global parameter T (called the temperature). The probability is large when the temperature is high so that the algorithm will not be stuck in a certain local optimum. On the other hand, the probability is low since the probability of local optima is low. When the temperature is zero, the algorithm reduces to the greedy algorithm. Typically this step is repeated until the system reaches a state that is good enough for the application, or until a given computation budget has been exhausted. The process of the Simulated Annealing is given in Table 4

Simulated-Annealing()

1: Create initial solution S

2: Initialize temperature t

3: **repeat**

4: **for** i = 1 to iteration-length **do**

5: Generate a random transition from S to Si

6: **if** (Objective_function(S) ≤ Objective_function(S_i))

7: then save the new best solution S_i to previous one S

8: **else**

9: Change state/solution with a random probability

10: Reduce temperature t

11: **until** (t=1)

12: **Return** S

Table 4 Simulated Annealing Algorithm pseudo-code

2.4.3. Genetic Algorithms

Finally, Genetic Algorithms (GA's) are search algorithms that work via the process of natural selection. They begin with a sample set of potential solutions, which then evolves toward a set of more optimal solutions. Within the sample set, solutions that are poor tend to die out while better solutions mate and propagate their advantageous traits, thus introducing more solutions into the set that boast greater potential (the total set size remains constant; for each new solution added, an old one is removed). A little random mutation helps guarantee that a set won't stagnate and simply fill up with numerous copies of the same solution. The pseudocode of Genetic Algorithm is presented in Table 5. In general, genetic algorithms tend to work better than traditional optimization algorithms because they're less likely to be led astray by local optima. This is because they don't make use of single-point transition rules to move from one single instance in the solution space to another. Instead, GA's take advantage of an entire set of solutions spread throughout the solution space, all of which are experimenting upon many potential optima. However, in order for genetic algorithms to work effectively, a few criteria must be met:

- It must be relatively easy to evaluate how "good" a potential solution is relative to other potential solutions.
- It must be possible to break a potential solution into discrete parts that can vary independently. These parts become the "genes" in the genetic algorithm.
- Finally, genetic algorithms are best suited for situations where a "good" answer will suffice, even if it's not the absolute best answer.

Genetic()

1: Choose the population S of random initializations

2: **repeat**

3: **for** i = 1 to iteration-length do

4: Generate a random populations from S to Si

5: **if** (Objective_function(S) ≤ Objective_function(S_i)) //Evaluate the fitness of each chromosome

6: **then** save the new best solution S_i to previous one S

7: **else**

8: Select pairs of best-ranking chromosomes to reproduce

9: Apply crossover operation

10: Apply mutation operation

11: **until** the Stop criteria

12: **Return** S

Table 5 Genetic Algorithm pseudo-code

2.5. Summary

This chapter elaborated on the design and implementation of a prototype hybrid system architecture that enables TVWS exploitation under both the Real-Time Secondary Spectrum Market and Spectrum of Commons policies, facilitating the inter- and intra-system communication respectively. It described a centralised infrastructure-based cognitive radio network based on RTSSM policy, where dynamic TVWS allocation among secondary systems was coordinated by a spectrum broker, which also administrated the economics of such transactions, related with TVWS leasing, utilising either fixed-price or auction-based policies. For efficient system performance, as a matter of maximum-possible radio resource exploitation and trading revenue, this chapter also elaborated on the study and development of a prototype RRM and Trading framework at the spectrum broker side, which was based on optimization methods and game theory concept to obtain best-matching solutions. Towards this, a RRM algorithm was designed, developed and incorporated in the proposed centralized CR networking architecture, enabling for efficient TVWS exploitation, providing QoS to secondary systems, while either minimizing spectrum fragmentation or maximizing Spectrum Broker profit.

The work carried out and described in this chapter, forms the basis towards the implementation of a prototype hybrid network architecture that conforms to the design and architectural specifications regarding the inter-system operation. Such an implementation is presented in chapter 3, where preliminary experimental tests for verifying the validity of the proposed architecture are also carried-out.

Part of the work presented in this chapter was published in [80], [81], [81], [83], [84], [85], [86], [87], [88], [89], [90].

3. PERFORMANCE EVALUATION AND EXPERIMENTAL RESULTS

3.1. Introduction

Following the hybrid system architecture, presented in chapter 2, this chapter elaborates on the implementation of a simulation scenario that conforms to the design specifications, towards verifying the validity of the proposed CR network architecture based on RTSSM policy, via a series of preliminary performance experiments. In this context, it presents the implementation of a Radio Resource Management and Trading framework as a process for the inter-system operation that enables for the opportunistic trading of un-used TVWS, by secondary systems (i.e. cellular/wireless network providers), respecting several constrains and guaranteeing QoS related requirements, like restrictions associated with maximum transmission power thresholds and possible interference. Towards addressing such challenges, TVWS leasing methods are anticipated, functioning into the central networking unit, namely spectrum broker. This unit operates by optimally assigning radio spectrum resources to secondary systems in specific geographical locations, according to a combinatorial auction-based process. Spectrum broker is able to enhance its revenue, by minimizing spectrum fragmentation, in case that a fixed-price policy is adopted, or maximizing revenues and radio spectrum exploitation efficiency, according to an auction-based policy. In this context, a number of preliminary experiments was designed and conducted under controlled conditions environment (i.e. simulation tests), elaborating on the overall system performance considering fixed-price and auction-based approaches. More specifically, and in the case of fixed-price, the experimental tests were conducted, in respect to spectrum fragmentation, spectrum utilization and simulation time. On the other hand, experimental tests, concerning auctions were conducted, in respect to spectrum broker benefit/utility, spectrum fragmentation, spectrum utilization and probability of accessing TVWS. Analysis of the experimental results, verified the validity of the proposed architecture in efficient spectrum allocation, fare and competitive sharing, establishing it as an alternative/complementary solution when extra spectrum is required to support high traffic.

3.2. Network Architecture Performance Evaluation

Towards verifying the validity of the proposed architecture and validating its capacity for efficient TVWS exploitation within the Real Time Secondary Spectrum policy (RTSSM), a set of experiments was designed and contacted under controlled-conditions environment. In this context, a simulation test-bed conforming to the overall design specifications (see Fig. 2-1) was set-up, comprising:

- A TVWS Occupancy Repository, hosting information about UHF/TV frequencies that can be exploited by Secondary Systems. The information in repository was built around actual/real spectrum data concerning the TVWS availability in Munich area, which have been acquired within the framework of the ICT-FP7 "CogEU" [76]. Following these actual/real data, Fig. 3-1 depicts the Maximum Allowable Power (MAP), at which a Secondary System may transmit within the range of TV channel 40 (626-632 MHz) to TV channel 60 (746-752 MHz). In this context, channels with "0" MAP (e.g. channel 44) represent frequencies occupied by Primary Systems (DVB-T), while those of "Low" MAP represent spectrum reserved for PMSE transmission (e.g. channel 45). Therefore, both these cases were not considered as available TVWS. On the other hand, in channels where "Max." MAP is permitted, Secondary Systems can be accommodated (e.g. channel 40, 50, 60, etc.). Thus the initial data within the TVWS Occupancy Repository comprised 10 UHF/TV (each one of 8MHz and total/aggregate bandwidth of 80MHz), scattered in the UHF spectrum according to Fig. 3-1.
- A number of Secondary Systems competing for TVWS exploitation, based on the LTE standard [91], [92]. The first set of simulation test exploit LTE systems, operating under the Frequency Division Duplexing (FDD) mode, utilising 5MHz bandwidth for the uplink channel (UL) and 5MHz for downlink one (DL), with an UL/DL-spacing of at least 1MHz. Furthermore, Time Division Duplexing (TDD) mode was chosen for the second set of simulation tests, utilising 5MHz bandwidth, while the transmission power of each LTE system in both cases was selected to be 4W.
- A Spectrum Trading and Policy Repository, hosting information about the TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading phase. It should be noted that in such experimental tests, the fixed-price policy was selected, based on a single spectrum-unit price that was applied for every TVWS frequency trading process.

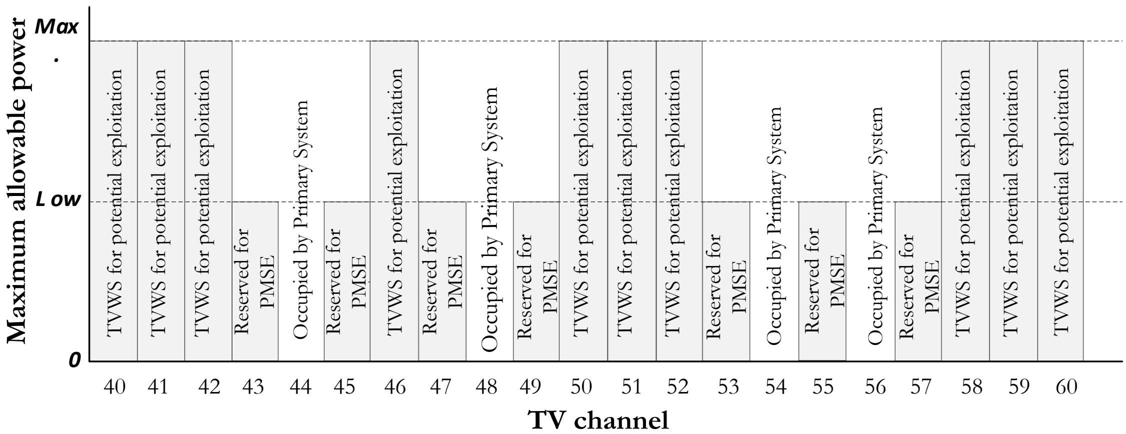

Fig. 3-1 Maximum allowable transmission power by secondary systems in TV spectrum for Munich area

Based on the described test-bed, a set of experiments was conducted, towards estimating the maximum number of LTE systems that can be efficiently accommodated under the RTSSM policy, as well as for evaluating the overall performance in respect to a) the number of possible allocation solutions explored before reaching the best-matching one and b) the spectrum utilization and the resulting spectrum fragmentation [93] when the best-matching solution is applied. Spectrum utilisation (see Equation 3-1) was estimated as the percentage of how much of the total bandwidth within TV channel 40 and TV channel 60 (i.e. 168MHz) is exploited/used, by both Primary and Secondary Systems:

$$Spectum\ utilisation\ (\%) = \frac{BW\ exploited\ by\ all\ systems\ (in\ MHz)}{168MHz}$$

Equation 3-1

Consequently, the initial condition in our tests comprised a spectrum utilisation of 19.04%. Additionally, spectrum fragmentation (or Fragmentation Score) was estimated by taking into account the number of unused spectrum-portions as well as the size of each individual fragment, according to Equation 3-2 [94],

$$Z = 1 - \frac{\sum_{i=1}^{n} f_i^p}{(\sum_{i=1}^{n} f_i)^p}$$

Equation 3-2

where "*n*" is the number of the scattered fragments (i.e. number of unused spectrum portions), "f_i" is the bandwidth of the *i*-th fragment (e.g. in MHz), while "*p*" is a constant, which in our experiments was equal to "2" as proposed in [94], .In such a case, it is evident that when Fragmentation Score (Z) is equal to "0" there is only fragment and therefore the spectrum is considered as un-fragmented, while as Z increases towards "1", the number of fragments also increases and the spectrum becomes more-and-more fragmented (many blocks of unexploited frequencies). Therefore, applying Equation 3-2 over the Munich frequency allocation pattern (see Fig. 3-1), an initial Fragmentation Score of **0.76817** was considered as the starting point for simulation tests.

During these performance evaluation experiments, the LTE systems were accessing the available TVWS in a sequential mode and not concurrently, i.e. for every new simulation-test (Time Period) an additional LTE system was entering the test-bed, requesting access to the available (at the given Time Period) TVWS frequencies. This means that every time a new LTE is assigned the requested spectrum (i.e. frequencies for UL and DL traffic for FDD or frequencies for DL traffic in case of TDD), the TVWS Occupancy Repository updates its data with the new spectrum allocation scheme, which in turn will be used during the next simulation test. Furthermore, and towards avoiding any interference between LTEs that are placed at consecutive frequencies, "frequency guard intervals" of 1MHz are utilised, one placed at upper-bound of an LTE's DL spectrum and another at its upper bound of the UL spectrum.

For example, and in case of the first scenario of FDD LTE systems, while in the Time Period 1 the first LTE requests frequencies from the initially available TVWS spectrum (i.e. from 80MHz), in Time Period 2 the new LTE requests access to the remaining frequencies, that is 68MHz available (i.e. 80MHz minus the 10MHz allocated to the 1st LTE along with the 2MHz of the "guard intervals" assigned to it). Fig. 3-2 below depicts the spectrum allocation scheme after the 1st Time period, i.e. when the first LTE is accommodated within the available TVWS, including the "guard intervals" placed at the upper bounds of the UL and DL portions. From this first simulation test (Time Period 1), the experimental results indicated a Fragmentation Score of **0.769148** and a Spectrum utilisation of **26.19%,** while the Simulated Annealing algorithm explored 120 possible allocation solutions before finding and applying the best-matching one.

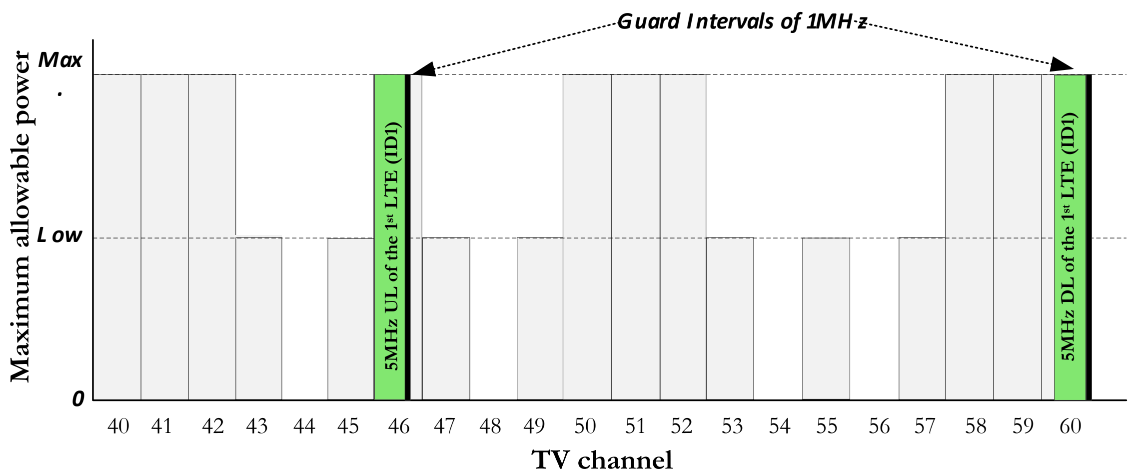

Fig. 3-2 Spectrum allocation the 1st LTE UL/DL channels, along with the corresponding "guard intervals", after the first Time Period

Similar simulation tests that were carried-out, towards exploiting the entire TVWS in the Munich spectrum-data (see Fig. 3-1), indicated that up-to 6 LTEs can be efficiently accommodated as secondary systems under the described RTSSM policy, resulting in an overall spectrum utilisation of **61.90%** and a Fragmentation Score of **0.889024.** Table 6 presents the experimental results for each of these simulation tests (Time Periods), where Time Period "0" represents the initial conditions, while Time Period 6 the case where the last LTE was accommodated. Fig. 3-3 illustrates the final placement of these 6 FDD LTEs within the Munich TVWS spectrum, while Fig. 3-4 presents the experimental results of LTE FDD scenario in figures.

Time Period	Spectrum Utilization (%)	Fragmentation Score	Number of solutions Explored
0	19.04%	0.76817	–
1	26.19%	0.769148	46
2	33.33%	0.766424	32
3	40.48%	0.764952	19
4	47.62%	0.771376	12
5	54.76%	0.863034	8
6	61.90%	0.889024	3
Total	–	–	120

Table 6 Experimental results when maximum number of LTEs FDD are accommodated in the Munich TVWS

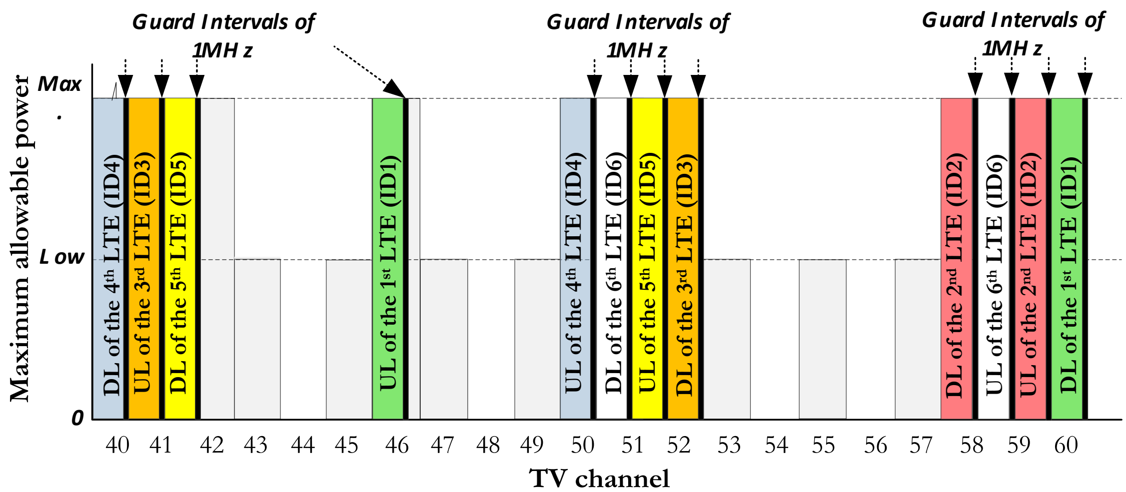

Fig. 3-3 Allocation of all LTEs FDD within the Munich TVWS

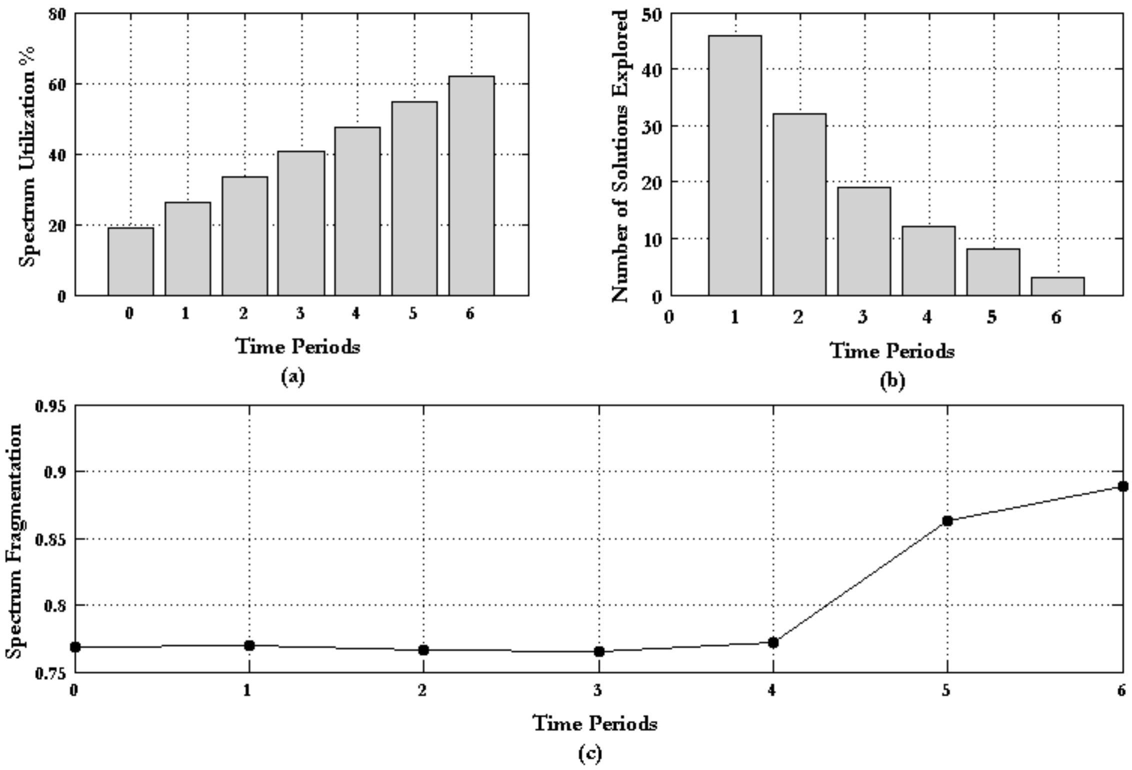

Fig. 3-4 Experimental results of LTEs FDD

On the other hand, and in the case of second scenario of TDD LTE systems, while in the Time Period 1 the first LTE requests frequencies from the initially available TVWS spectrum (i.e. from 80MHz), in Time Period 2 the new LTE requests access to the remaining frequencies, that is 74MHz available (i.e. 80MHz minus the 5MHz allocated to the 1st LTE along with the 1MHz of the "guard intervals" assigned to it).

Similar simulation tests that were carried-out, towards exploiting the entire TVWS in the Munich spectrum-data (see Fig. 3-1), indicated that up-to 13 TDD LTEs can be efficiently accommodated as secondary systems under the described RTSSM policy, resulting in an overall spectrum utilisation of **57.74%** and a Fragmentation Score of **0.89109.** Table 7 presents the experimental results for each of these simulation tests (Time Periods), where Time Period "0" represents the initial conditions, while Time Period 13 the case where the last LTE was accommodated, utilizing the Simulated Annealing algorithm. Fig. 3-5 illustrates the final placement of these 13 TDD LTEs within the Munich TVWS spectrum, while Fig. 3-6 presents the experimental results of LTE TDD scenario in figures.

Time Period	Spectrum Utilisation (%)	Fragmentation Score	Number of solutions Explored
0	19.05%	0.76817	–
1	22.02%	0.77292	62
2	25.00%	0.77312	55
3	27.98%	0.77358	50
4	30.95%	0.76962	44
5	33.93%	0.76000	38
6	36.90%	0.80865	36
7	39.88%	0.81737	29
8	42.86%	0.82118	24
9	45.83%	0.81826	20
10	48.81%	0.87750	13
11	51.79%	0.89102	6
12	54.76%	0.89681	4
13	57.74%	0.89109	2
Total	–	–	383

Table 7 Experimental results when maximum number of LTEs are accommodated in the Munich TVWS

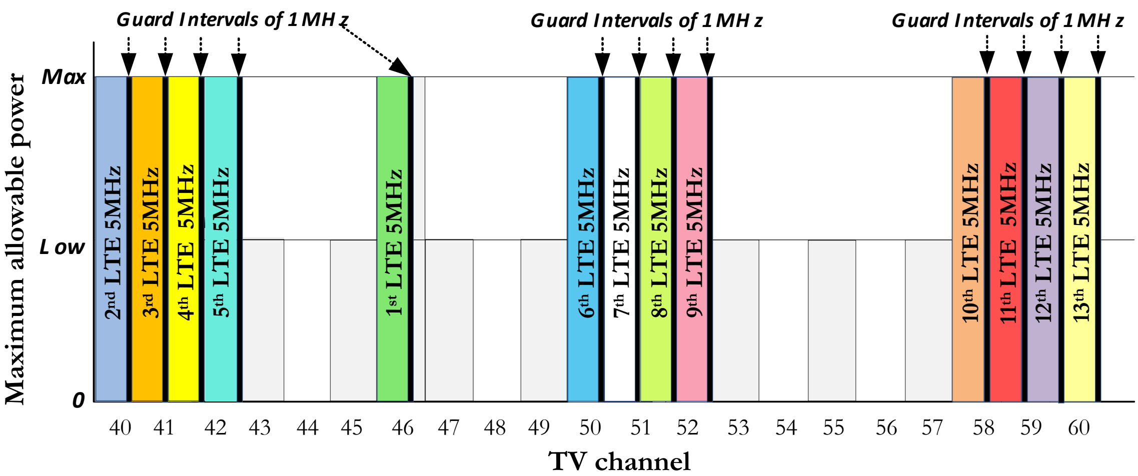

Fig. 3-5 Allocation of all LTEs TDD within the Munich TVWS

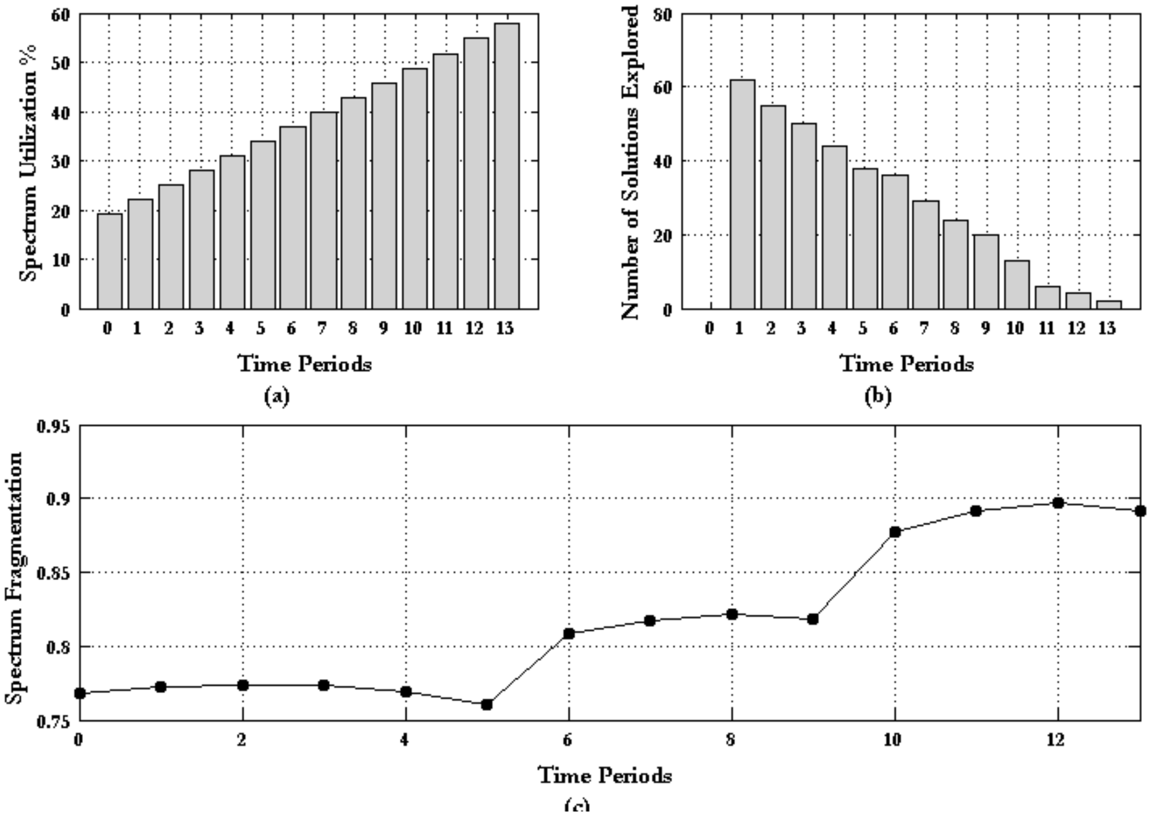

Fig. 3-6 Experimental results of LTEs TDD

3.3. Performance Evaluation of the Optimization Algorithm

Towards verifying the validity of the proposed CR architecture and evaluating its capacity for efficient TVWS exploitation within the RTSSM policy, three versions of the proposed decision-making process are implemented: the first one by exploiting the Backtracking algorithm and Pruning feature, the second one by utilising the Simulated Annealing and the third one by developing the Genetic Algorithm [37].

In this context, a number of experiments were designed and conducted under controlled-conditions (i.e. simulations) concerning the performance of the above algorithms, as a function of the number of secondary systems that each algorithm can accommodate, the resulted spectrum utilization and frequency fragmentation [94], the time needed to provide the best-matching solution, as well as for obtaining qualitative comparison results among the three RRM implementations. The experimental test-bed comprised of a TVWS Occupancy Repository providing an initial spectrum utilisation of **19.05%** and featuring a fragmentation of about **0.76817**, a Spectrum Trading and Policy Repository hosting information regarding the spectrum unit price, as well as a number of Secondary Systems. These systems require access to TVWS with different radio characteristics/requirements and simultaneously compete for the available TVWS. Such systems exploit LTE [91], [92] operating with Time-Division-Duplexing (TDD), WiFi [96] and Public Safety [97] technologies. For each one of the above mentioned secondary systems, a different QoS-level requirement was selected, thus the optimisation algorithm was also taking into account this parameter during the spectrum allocation process under a real-time procedure. More specifically, requests of secondary systems are received and processed in real-time, by spectrum broker, which identifies their technical characteristics and provides an immediate response respecting the QoS constraints. Additionally, for every new time period of the simulation, the secondary systems were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS frequencies. The technical specifications of the secondary systems are presented in Table 8.

TABLE I
TECHNICAL SPECIFICATIONS OF EACH SECONDARY SYSTEM

Service Type	Power (Watt)	Bandwidth (MHz)	Priority/QoS Requirement
LTE 1	4	20	Medium
LTE 2	4	10	Medium
LTE 3	4	20	Medium
LTE 4	4	5	Medium
WiFi 1	0.25	22	Low
WiFi 2	0.25	22	Low
WiFi 3	0.25	22	Low
Public Safety 1	0.1	1	High
Public Safety 2	0.1	1	High

Table 8 Technical Specifications of each Secondary System

Based on this test-bed, five time periods were designed and conducted as follows:

- Time Period 1: “LTE 1” system is requesting access to TVWS up to time period 2.
- Time Period 2: “LTE 1” maintains access to the spectrum, while two new secondary systems “Public Safety 1” and “WiFi 1” are requesting access to the spectrum up to time periods 5 and 4, respectively.
- Time Period 3: “LTE 1” releases the occupied spectrum as well as the “Public Safety 1” and “WiFi 1” maintain their access to TVWS. Also, two new secondary systems (“LTE 2” and “Public Safety 2”) are accessing the available spectrum up to time period 5.
- Time Period 4: “Public Safety 1”, “WiFi 1”, “LTE 2” and “Public Safety 2” are still operating, while two new secondary systems, “LTE 3” and “WiFi 2”, are accessing the available spectrum, up to time period 5.
- Time Period 5: “WiFi 1”, “WiFi 2” and “LTE 3” release the occupied TVWS, while “Public Safety 1”, “Public Safety 2” and “LTE 2” are still operating. During this time period “LTE 4” and “WiFi 3” systems are requesting access to the spectrum.

Fig. 3-7 (a) depicts the results obtained in every Time Period for each RRM implementation, where the initial value of the spectrum utilization is **19.05%,** i.e. when only primary systems operate in the TVWS channels. From this figure it can be verified that all-four algorithms result in the same spectrum utilisation (for each Time Period), given that the same number of secondary systems was accommodated. Spectrum fragmentation was calculated, by taking into account the number of fragments (unused spectrum-portions) as well as the size/bandwidth of each individual fragment, as it is presented in Equation 3-2. Fig. 3-7 (b) depicts the results obtained in every Time Period for each RRM implementation, where initial condition resulted to a spectrum fragmentation of **0.76817** when no secondary system is accommodated. From this figure it can be verified that all algorithms provide an acceptable fragmentation score, taking into account that: a) the value "0" represents an "un-fragmented" spectrum, while when moving towards "1" the spectrum becomes more-and-more fragmented, i.e. there exist many blocks of unexploited frequencies. Finally, Fig. 3-7 (c) represents a qualitative comparison among Backtracking (with and without Pruning technique), Simulated Annealing and Genetic algorithms, as a matter of the duration of the simulation before obtaining the optimum solution. Considering this plot, it can be observed that Simulated Annealing performs slightly better in comparison to the other algorithms, obtaining faster the best-matching solution in a shorter simulation time. Finally, Fig. 3-7 (c) presents the simulation time of the proposed algorithms. Simulated Annealing and Genetic Algorithm perform better than Backtracking one, while the Pruning technique alleviates their differences.

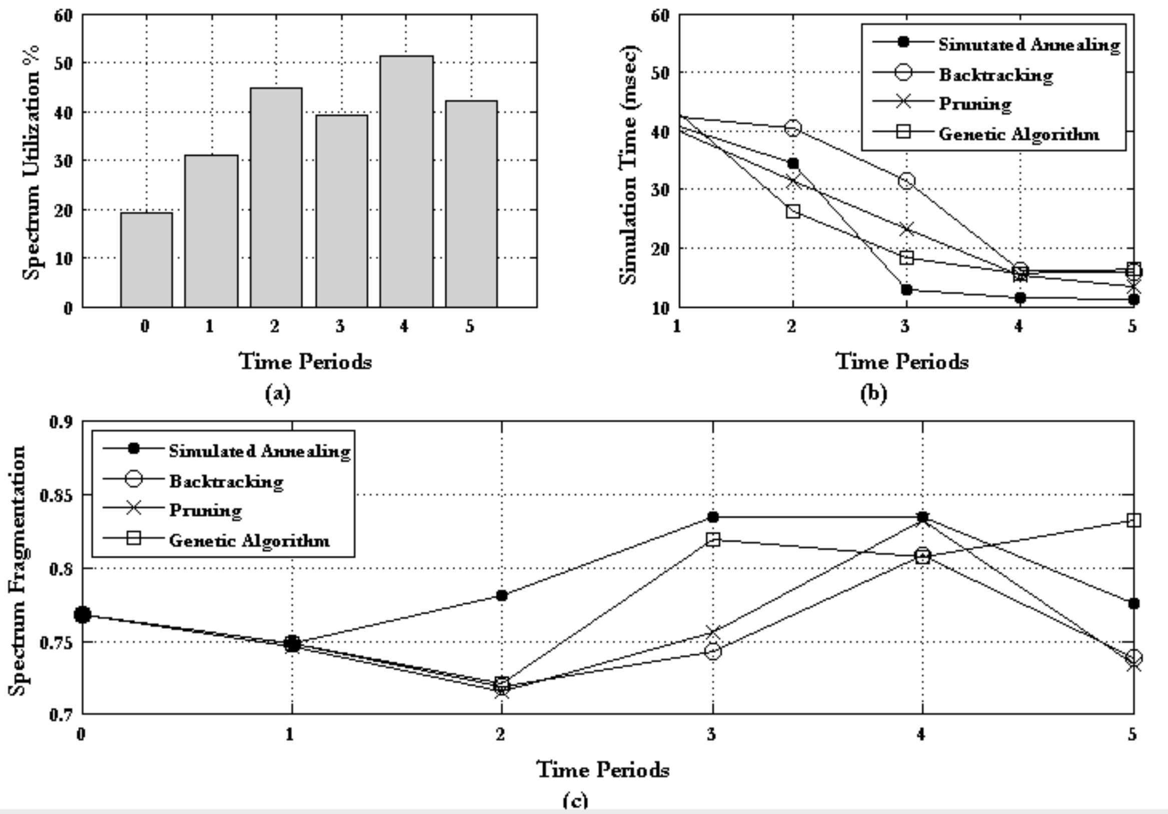

Fig. 3-7 Experimental results comparison of optimization algorithms

Additionally to the above results, a very interesting outcome is related to the broker's capability in accommodating secondary systems when the available TVWS spectrum is shorter than the total requested bandwidth, and therefore only part of the competing systems can be served. In such a case, the broker takes into account the priority level of each secondary system, and grants access only to those of the highest level. For example, during Time Period 4, there are already four secondary systems active (i.e. "Public Safety 1", "WiFi 1", "LTE 2" and "Public Safety 2"), and the total available spectrum sums about 32MHz, scattered within TV channel 46, 58, 59 and 60 (see Fig. 3-8). For this spectrum two more secondary systems are competing, i.e. "LTE 3" of medium priority level requesting 20MHz, and "WiFi 2" of low priority level requesting for 22MHz. Evidently, while both "LTE 3" and "WiFi 2" are competing for the spectrum within channel 58 to channel 60, only one of them is served, i.e. that of the higher priority ("LTE 3").

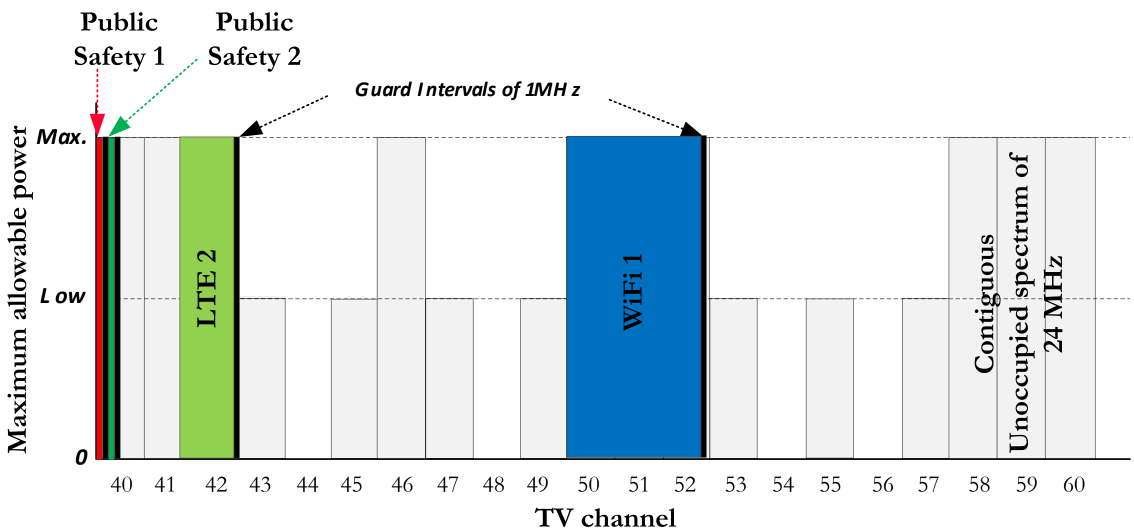

Fig. 3-8 TVWS allocation during the Time Period 4

3.4. Performance Evaluation for QoS Provision

Towards verifying the validity of the proposed CR network architecture and evaluating its capacity for efficient TVWS exploitation and QoS provisioning within the RTSSM policy, a decision making process was implemented by exploiting Simulating Annealing Algorithm. In this context, several sets of experiments were designed and conducted under controlled-conditions (i.e. simulations) evaluating the performance of the above algorithm, in one hand, as a matter of the number of secondary systems that can be accommodated, the resulted spectrum utilization and frequency fragmentation, while on the other hand as a matter of LTE secondary systems service rate and the percentage of spectrum broker benefit. The experimental test-bed, providing an initial spectrum utilisation of **19.05%** and featuring a fragmentation of about **0.76817**, only when primary systems are considered. It should be noted that in the simulation tests that were conducted, both fixed-price and auction-based modes were selected, based on a single spectrum-unit price that was applied for every TVWS frequency trading process.

This simulation scenario includes five LTE Secondary Systems with different radio characteristics that were simultaneously competing for the available TVWS. These systems were based on LTE, operating under Time-Division-Duplexing (TDD) mode, while a different QoS level was adopted for each system, based on specific services requirements. This QoS level was respected, by the optimisation algorithms for both fixed-price and auction-based mode, during spectrum allocation process. Additionally, for every new simulation period (namely as Time Period in the experimental tests) secondary systems with different QoS expectation were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS. The technical specifications of such LTE secondary systems are presented in Table 9.

Secondary System	Services Provided	Bandwidth (MHz)	Priority/QoS Level
LTE 1	TCP-based services (GBR)	20	Medium
LTE 2	P2P (Non-GBR)	5	Low – Best Effort
LTE 3	Internet (Non-GBR)	20	Low – Best Effort
LTE 4	Video (GBR)	20	High
LTE 5	Video (GBR)	5 -10	High

Table 9 Technical Specifications of each Secondary System

From Table 9 it comes that there are two major types of services provided with guaranteed bit rate (GBR) and non-guaranteed bit rate (Non-GBR). GBR services are real-time applications, such as conversational voice and video, while Non-GBR services include P2P and Web applications. For a GBR service, a minimum amount of bandwidth is reserved by the system and the network resources provision is guaranteed, by taking into account specific QoS requirements. GBR services should not experience packet losses or high latency in case of network congestion. On the other hand, Non-GBR services are provided under a best effort scheme and a maximum bit rate is not guaranteed on a per-service basis. Based on the above mentioned simulation scenario, four time periods (see Table 10) were defined as follows:

	Time Period 1	Time Period 2	Time Period 3	Time Period 4
LTE 1	√	√	√	√
LTE 2	√	√	√	–
LTE 3	–	√	√	√
LTE 4	–	√	√	√
LTE 5	–	–	√	√

Table 10 Time Periods of Simulation Scenario

- Time Period 1: “LTE 1” and “LTE 2” systems are requesting access to TVWS up to time period 4 and 3, respectively.
- Time Period 2: “LTE 1” and “LTE 2” maintain access to the spectrum, while two new secondary systems “LTE 3” and “LTE 4” are both requesting access to the spectrum up to time period 4.
- Time Period 3: “LTE 1”, “LTE 2”, “LTE 3” and “LTE 4” maintain their access to TVWS, while an additional secondary system “LTE 5” is accessing the available spectrum up to time period 4.

Time Period 4: Four LTE systems are operating and a higher services provision demand stemming from “LTE 5” terminals, creates the need for more traffic resources for this specific LTE secondary system.

Table 11 summarizes the results obtained in every Time Period, by exploiting the RRM algorithm. Table 11 also presents the initial value of the spectrum utilization, i.e. when only primary systems operate in the TVWS channels. Spectrum fragmentation was calculated, by taking into account the number of fragments (i.e. unused spectrum-portions), as well as the size/bandwidth of each individual fragment, as it is presented in Equation 3-2. Table 11 summarizes the results obtained in every Time Period, where the initial condition is also shown, when no secondary system is accommodated. From these results, it can be verified that the proposed algorithm provides an acceptable fragmentation score, taking into account that: a) the value “0” represents an “un-fragmented” spectrum, while when moving towards “1” the spectrum becomes more-and-more fragmented, i.e. there exist many blocks of unexploited frequencies.

Table 11 presents the results obtained for each Time Period according to the simulation tests:

- Time Period 1: Two secondary systems are requesting for 20MHz and 5MHz respectively. A spectrum fragmentation of 14.88% and a fragmentation score of 0.75513 was obtained.
- Time Period 2: Four secondary systems are requesting for 20MHz, 5MHz, 20MHz and 20MHz respectively. In this case, spectrum utilization is 38.69%, while fragmentation score is 0.85658.
- Time Period 3: Five secondary systems are requesting access to TVWS increasing spectrum demand. In such a case, Spectrum broker allocates the available TVWS, respecting QoS requirements. More specifically, “LTE 5” is served with a higher priority, than “LTE 2”, which operates under a best-effort mode. Spectrum utilization is 38.69% and fragmentation score is 0.85658 at this time period.
- Time Period 4: In this time period, “LTE 5” is requesting for more traffic resources and exploits 10MHz instead of 5MHz. For this scope, spectrum broker assigns the extra available spectrum, respecting QoS priority. In this case, “LTE 3” that operates, exploiting 20MHz under a best-effort mode, releases the spectrum, which is then assigned to “LTE 5”. This allocation process results a spectrum utilization of 29.76%, and a fragmentation score of 0.80341.

Time Period	Spectrum Utilisation (%)	Fragmentation Score	Number of LTE SS Accommodated
0	19.05%	0.76817	-
1	14.88%	0.75513	2
2	38.69%	0.85658	4
3	38.69%	0.85658	4
4	29.76%	0.80341	3

Table 11 Experimental results for each Time Period under the Number of accommodated Secondary Systems

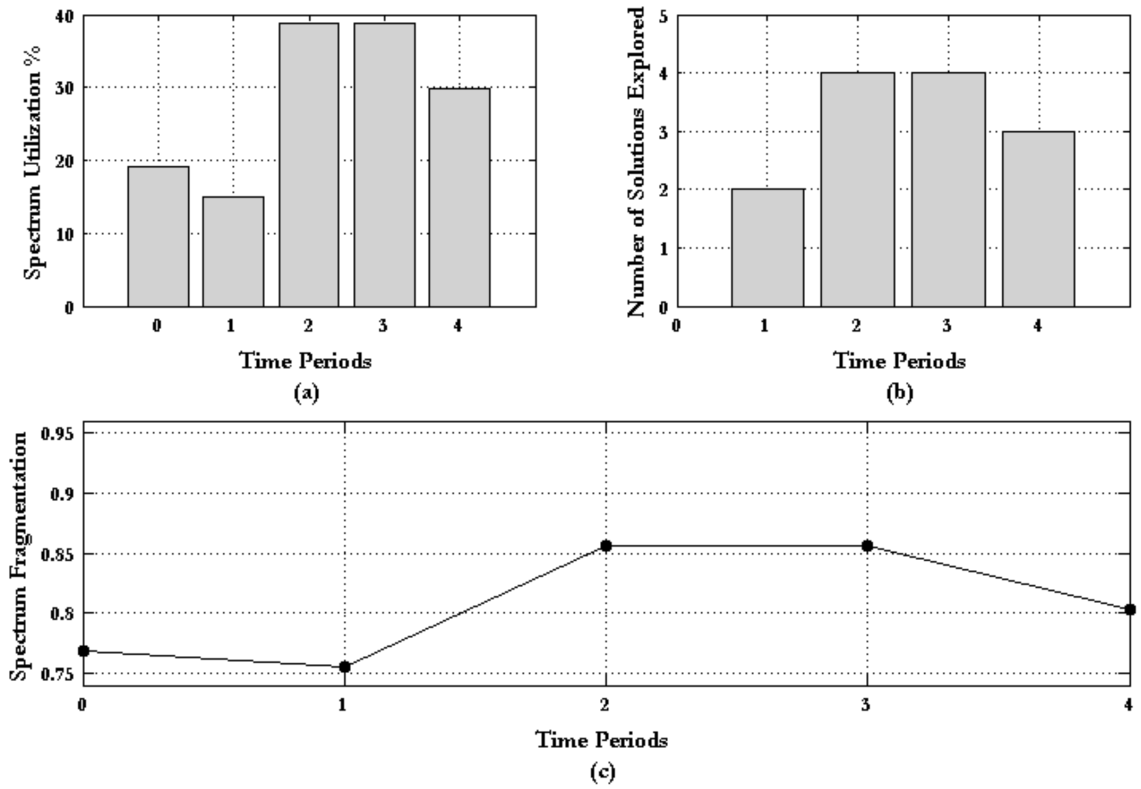

Fig. 3-9 Experimental results of Secondary Systems

Additionally to the above performance evaluation results, a quantitative and qualitative comparison of both proposed RRM algorithms is next provided, in terms of spectrum broker benefit and secondary systems service rate. More specifically, the upper diagram of Fig. 3-10 depicts spectrum broker benefit for both RRM algorithms (i.e. auction-based and fixed mode). It can be observed that spectrum broker benefit is increasing when the number of LTE secondary systems concurrently accessing TVWS channels, is increasing during all time periods of the above mentioned simulation scenario. Furthermore, auction-based mode provides an optimized performance, in terms of spectrum broker benefit (i.e. increased percentage), in comparison to fixed-price mode. The lower diagram of Fig. 3-10 represents the service rate of all secondary systems for both allocation processes (i.e. algorithms). It can be observed that the proposed spectrum broker and RRM algorithms respect QoS requirements of secondary systems, according to the simulation scenario defined above.

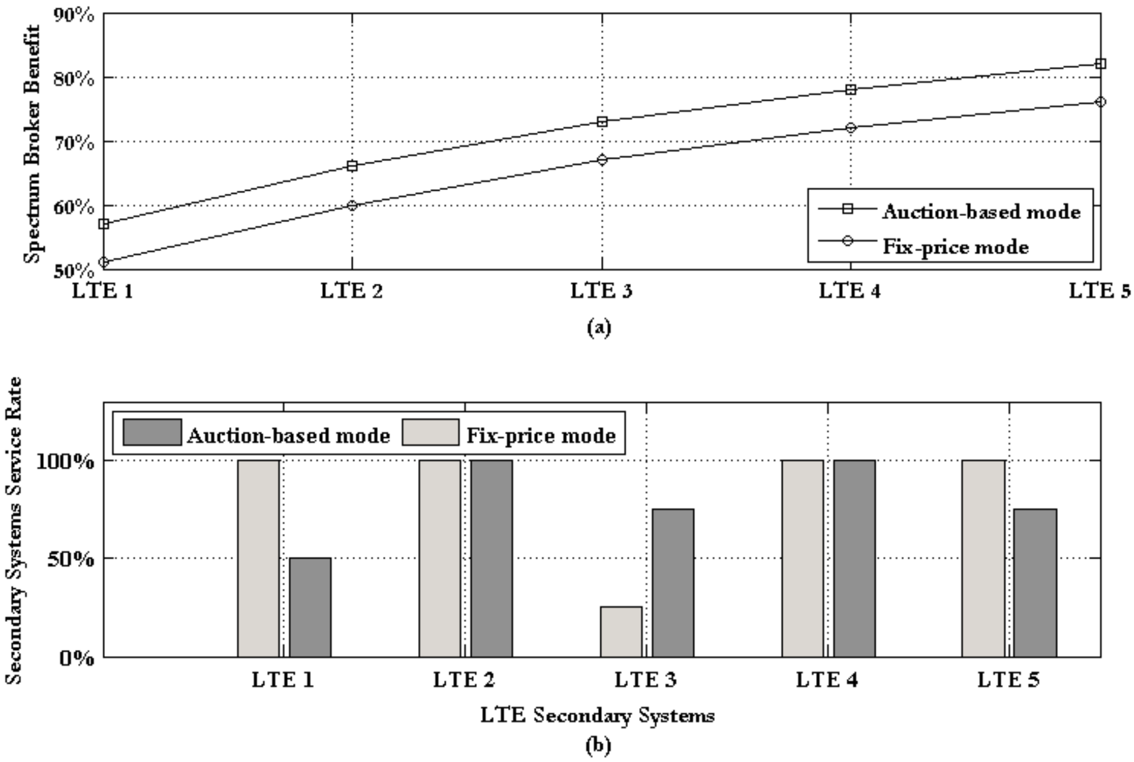

Fig. 3-10 Experimental results comparison of Fix and Auction approaches

3.5. Performance Evaluation - Quantitative and Qualitative Comparison of Spectrum Broker pricing models

Towards verifying the validity of the algorithms, for different pricing models (i.e. fixed-price approach and auction-based process), a set of experimental test was designed and conducted. A simulation test-bed, based to the overall design specifications was set-up, comprising four time-auctions/allocation per hour, (each one of 15-minutes long intervals). The available TVWS based on real data [76] are ten, while the number of frequency-time slots is forty. They are computed, by multiplying available TVWS and time-auctions per hour. Moreover, the number of competitive secondary systems was up to fifty base stations, exploiting LTE technology, thus the same number of TVWS can be leased/allocated to more than one LTE base station, based on the re-used distance and on condition that no interference is caused. Both price models allow a player to reserve radio spectrum with temporarily exclusive rights for longer than the next time slot. The winners obtain these rights for the allocated spectrum until the next auction. The valuation of spectrum (i.e. 1MHz) in both cases was resulted, considering a number of parameters [77], [95], such as benchmark price, price factor over year, population density, allocation area, degree of competition, incentives of operators in low/medium/high density areas and traffic conditions (i.e. low/medium/high).

Performance of the proposed research approach was evaluated, considering a quantitative and qualitative comparison among both algorithms, in order to estimate the average values of spectrum broker benefit/utility, spectrum fragmentation, spectrum utilization and probability of accessing TVWS, according to RTSSM policy. More specifically, spectrum broker benefit was estimated based on the total income by secondary systems during four spectrum leasing time periods. Fig. 3-11 presents the average benefit/income of spectrum broker, under various numbers of bidders (i.e. LTE secondary systems) for both algorithms during all time periods (i.e. four experimental tests were conducted). It is observed that the proposed algorithm based on the auction process performs better providing higher revenue compared to the fixed-price algorithm.

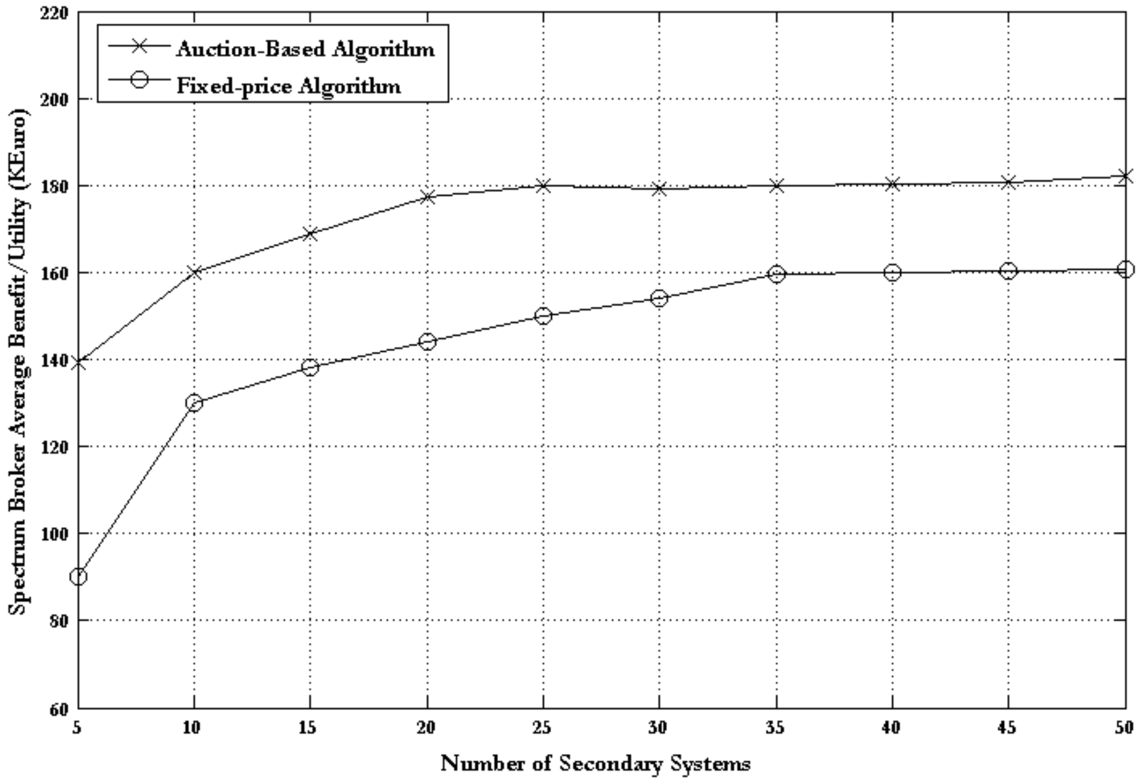

Fig. 3-11 Spectrum Broker Average Benefit

Moreover, spectrum utilization was estimated as the percentage of the exploited bandwidth over the totally available TVWS, while spectrum fragmentation was estimated, by considering the unused parts of radio spectrum and the size for each individual fragment. In cases that spectrum fragmentation is equal to "0", radio spectrum is considered as un-fragmented after the allocation process, while as the value increases towards to "1", the number of fragments left after the assigning process, are increased and spectrum becomes more-and-more fragmented (i.e. many blocks of unexploited frequencies exist after TVWS allocation process). It has to be noted here that towards avoiding possible interference among LTE secondary systems assigned with consecutive channels, frequency parts of 1MHz are left un-used as guard intervals. As the number of secondary systems is getting higher, the number of guard intervals also increases, resulting to a higher radio spectrum fragmentation, after frequency allocation process. Fig. 3-12 and Fig. 3-13 present evaluation results, regarding average spectrum utilization and spectrum fragmentation respectively. As spectrum utilization is increasing, resulting to an increased number of secondary systems that exploit TVWS, fragmentation is also increasing, getting worst. In case of the fixed-price algorithm, the most optimum solution is provided, based on minimizing spectrum fragmentation, resulting to lower levels of utilization. On the other hand, auction-based algorithm creates a more fragmented radio spectrum after the allocation process, when the number of secondary systems served, is higher in comparison to the fixed-price algorithm.

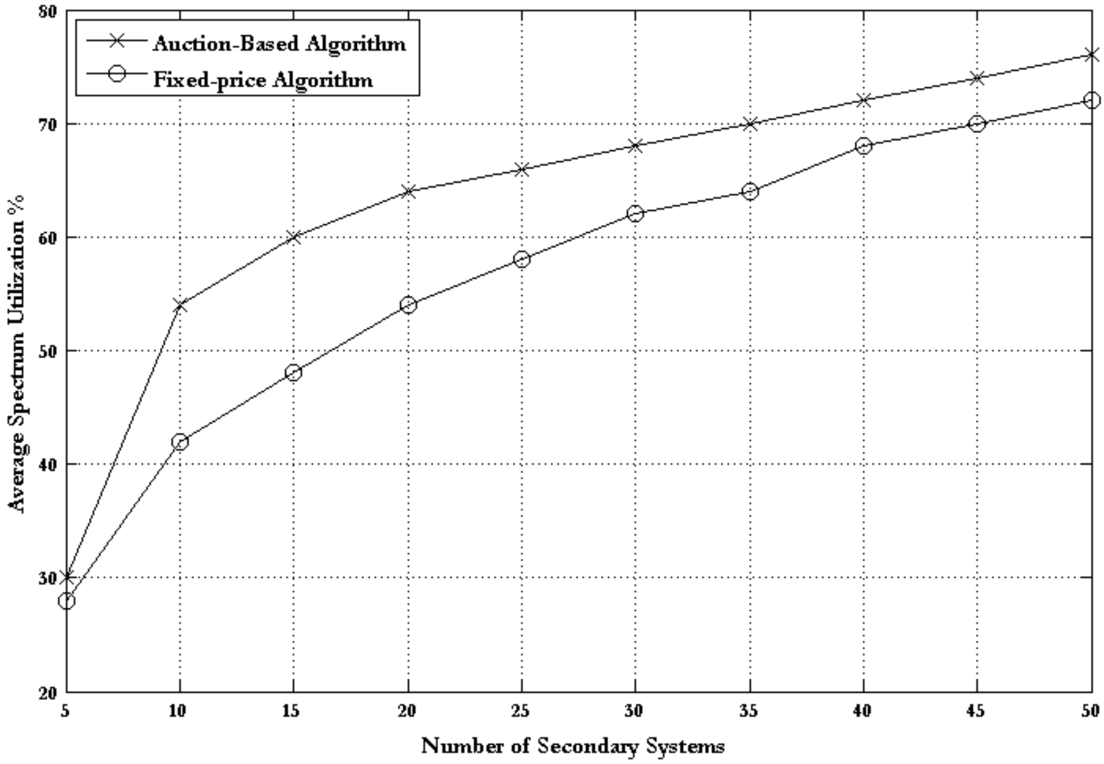

Fig. 3-12 Average Spectrum Utilization

Finally, probability of accessing TVWS is a metric that defines the possibility of a secondary system permitted to operate, exploiting radio spectrum resources. The auction-based algorithm provides a higher probability of using TVWS, in comparison to the fixed-price algorithm, as depicted in Fig. 3-14. This implies that bidders are encouraged to participate in the auction-based process, increasing the possibility to access the available TVWS.

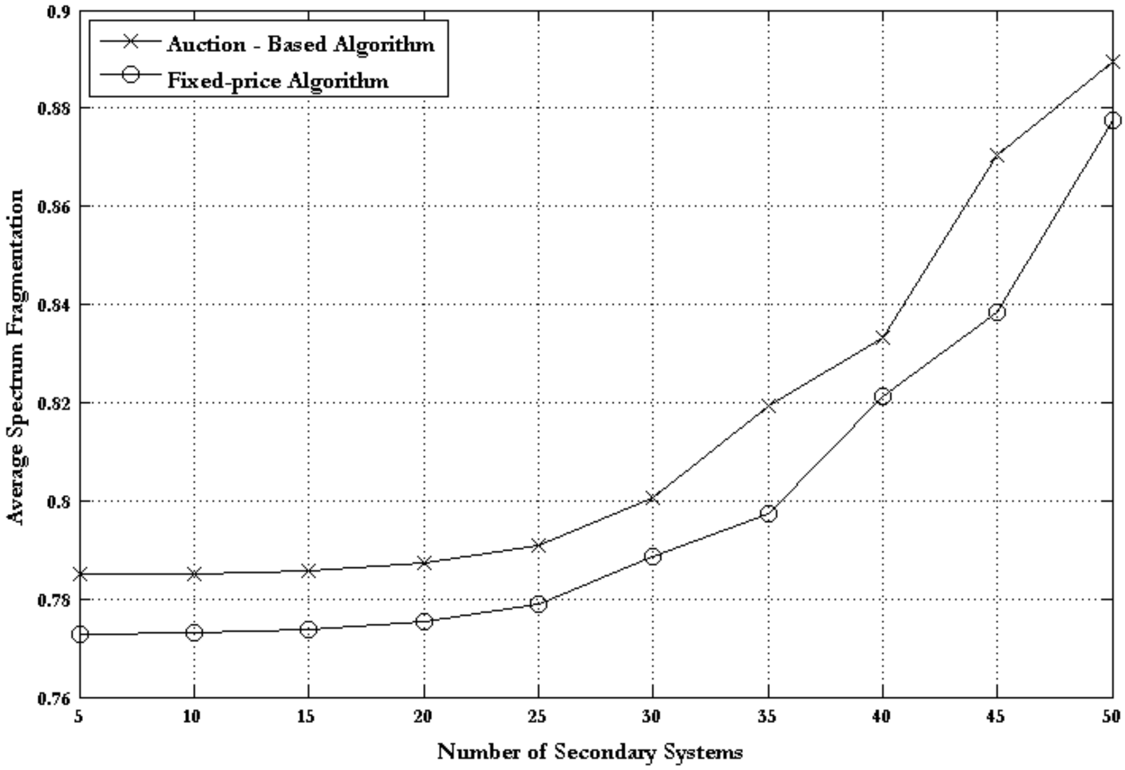

Fig. 3-13 Average Spectrum Fragmentation

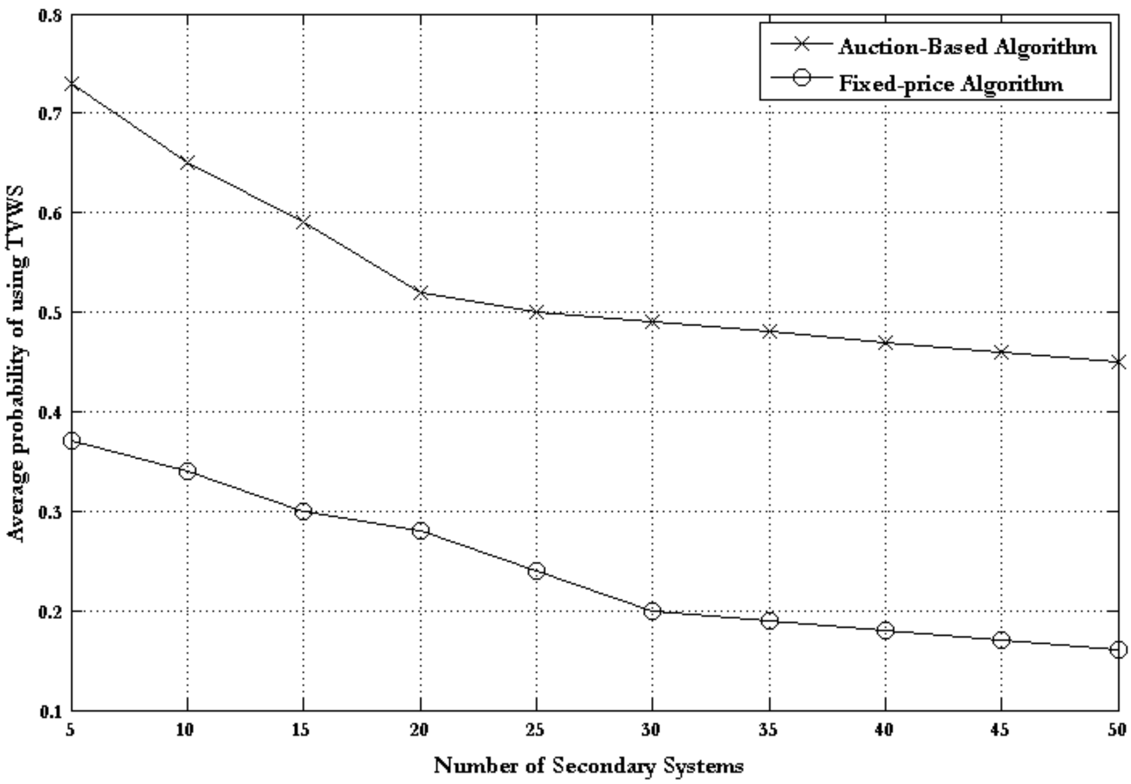

Fig. 3-14 Average Probability of accessing TVWS

3.6. Summary

This chapter presented the realisation of a number of simulation scenarios that conformed to the network design specifications, as these were defined in chapter 2, which exploited an infrastructure-based CR network, where dynamic TVWS allocation among secondary systems was coordinated by a spectrum broker entity. In this context, the implementation of a Radio Resource and Trading framework was presented to enable inter-system operation of the proposed hybrid architecture, for TVWS allocation among secondary systems, where a spectrum broker entity administrated economic issues of transactions, related with TVWS leasing. This framework was served as a testbed for verifying the validity of the proposed architecture and its capacity in providing optimal and fare TVWS allocation solutions among secondary systems. In this respect, a number of preliminary experiments were designed and conducted under controlled conditions regarding fixed-price or auction-based algorithms.

More specifically, and in the case of fixed-price, the spectrum broker reached to the most optimal allocation solution, by minimizing an objective function, as a matter of allowable transmission power, requested bandwidth, spectrum fragmentation, when a secondary system was assigned to a specific frequency and/or secondary systems prioritization (e.g. in case that a number of secondary systems must be served before other ones, due to higher QoS level priority). Spectrum fragmentation, spectrum utilization and simulation time were chosen as the metrics for evaluation, under the different simulation conditions. It was experimentally verified that all-four algorithms resulted to the same spectrum utilisation, given that the same number of secondary systems was accommodated, while the Spectrum fragmentation was slightly increasing, as the number of secondary systems that were accessing the spectrum was getting higher. Moreover, by a qualitative comparison among RRM implementations it was observed that Simulated Annealing performs slightly better in comparison to the other algorithms, obtaining faster the best-matching solution in a shorter simulation time, while in case of simulation time, Simulated Annealing and Genetic Algorithm performed better than Backtracking one, as well as the Pruning technique alleviated their differences. On the other hand, the preliminary tests concerning auctions were conducted, in order the spectrum broker to determine the optimal allocation solution, considering the maximization of its own income. To occur this, spectrum broker undertook the trading mechanism that was collecting bids from secondary systems, in order to lease radio spectrum, taking into account spectrum broker benefit/utility, spectrum fragmentation, spectrum utilization and probability of accessing TVWS. It was experimentally verified that, the auction-based approach performed better considering the spectrum broker welfare, while the fixed-price approach was a more stable solution considering the spectrum fragments. Analysis of the experimental results, verified the validity of the proposed architecture in efficient spectrum allocation, fare and competitive sharing, establishing it as an alternative/complementary solution when extra spectrum was required to support high traffic.

Part of the work presented in this chapter was published in [80], [81], [81], [83], [84], [85], [86], [87], [88], [89], [90].

4. ROUTING PROTOCOLS IN COGNITIVE RADIO NETWORKS

4.1. Introduction

This chapter elaborates/focuses on the study, development and experimental evaluation of a novel routing protocol (i.e. network-layer process), allowing communication among ad-hoc secondary users (i.e. CR devices). The proposed routing scheme is designed for ad-hoc CR constellations, where each communicating party is placed at different/isolated TVWS allotments, i.e. no direct communication link exists between the corresponding CR users. For these reasons, the proposed routing protocol encompasses mechanisms that take into account the system topology (in an end-to-end approach) prior to establish the best routing path. The case of ad-hoc network topology for efficient inter-system communication based on Spectrum of Commons, is of particular research interest, regarding the optimum establishment of routing paths. In such a case secondary nodes must be adaptive to the dynamic changes in spectrum utilization by primary users. Thus, routing in the proposed hybrid CR network architecture is diverse from routing in conventional wireless networks and particularly in multi-channel networks, in which static sets of channels are available for communication nodes [57], [58]. Secondary nodes exploit alternative sets of available channels that impose several routing challenges especially in multi-hop communication [54], [59]. For this reason, routing has to be spectrum aware, while routing schemes for conventional wireless networks cannot be efficiently applied [55], [56], [57], [60], [61] and [62]. A number of research approaches elaborate with challenges of routing process in CR networks, such as in [63], where a routing protocol is exploited to combine geographical routing and radio spectrum assignment, towards avoiding regions with high presence of primary communication nodes. It also determines optimum routing path channel combinations that reduce delays in the network. A spectrum aware data adaptive routing algorithm is proposed in [64], where the end-to-end route selection depends on the amount of data to be transferred. Furthermore, the proposed routing protocol in [65] builds a forwarding mesh based on a set of available routes to the destination and opportunistically adapts during the forwarding process, according to the dynamic radio spectrum conditions. Moreover, a joint approach of on-demand routing and spectrum band selection is proposed in [66] for CR networking environments and a delay based metric is used to evaluate the quality of alternative routes. Most of the previous schemes are based on on-demand routing protocols and discover paths between source and destination communication nodes.

However, none of the above mentioned approaches considers a heterogeneous radio spectrum environment, where secondary nodes cannot obtain a permanent common control channel, as TVWS vary in time and space. Moreover, secondary nodes that establish an ad-hoc mesh network, operating under the Spectrum of Commons policy [67], [68] cannot guarantee QoS, thus route maintenance is difficult to be obtained. The proposed routing protocol, presented in this chapter, implements a mechanisms at each secondary user that considers traffic redirection and load balancing issues, in order to determine though hop-by-hop evaluation which neighbouring node performs better in the routing path, or for mitigating traffic in cases of overloading. This routing approach is evaluated in terms of several delay metrics, in order to validate the efficient inter-system operation of the proposed hybrid network architecture.

4.2. Routing Scheme Using Optimal Paths

Transmission of secondary communication nodes in the inter-system operation of the proposed hybrid CR network architecture is based on radio spectrum opportunity, where routing has to take into account the availability of spectrum in specific geographical locations at local level. Spectrum awareness, route quality and route maintenance issues have to be investigated for different routing schemes, in order to enable for efficient data transfer, across regions with heterogeneous radio spectrum availability, even when the network connectivity is intermittent or when an end to end path is temporarily unavailable. Fig. 4-1 illustrates in more detailed the inter-system topology of CR network architecture (see Fig. 2-1), where primary systems operate over specific channels in three geographical areas (i.e. Area A, B and C in Fig. 4-1). Secondary nodes opportunistically operate, by utilizing remaining available channels in each geographical area (i.e. TVWS in Fig. 4-1). It has to be noted here that a stable/permanent CCC does not exist between secondary nodes, which are located in neighbouring geographical areas (i.e. Area A, B and C in Fig. 4-1). In this case, all secondary communication nodes operate as intermediate relay nodes, switching between alternative channels. Therefore, such relay nodes enable for ad-hoc connections among secondary nodes, located inside areas A, B and C.

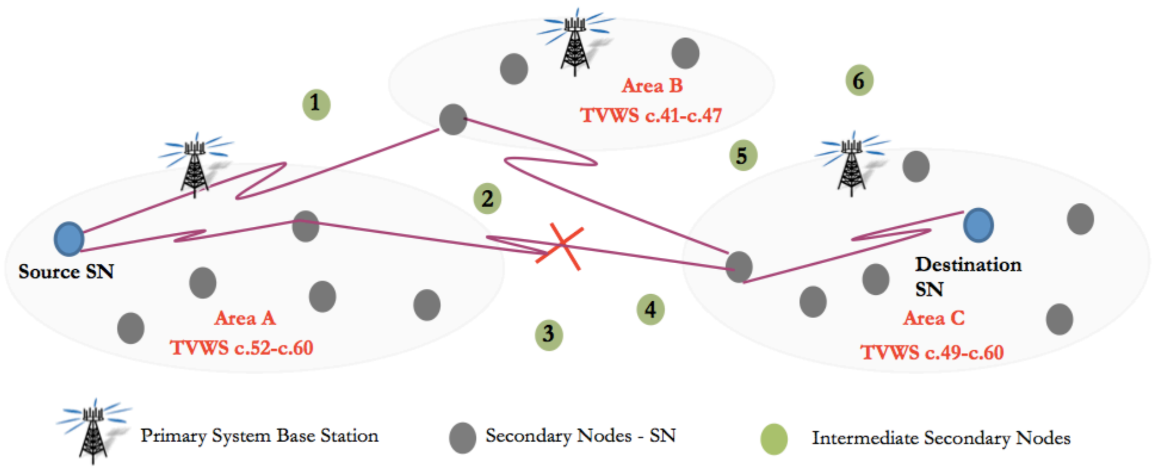

Fig. 4-1 Secondary communication nodes operating over heterogeneous TVWS.

Taking into account the above mentioned scenario, spectrum awareness has to be investigated, regarding routing in such an ad-hoc CR network, where secondary nodes are prohibited to operate on spectrum bands occupied by primary nodes. The main target of routing in this CR networking environment is to provide optimal, high throughput data transfer by efficiently selecting the best routing paths among secondary nodes. Thus, multi-hop connections must be set up between secondary users pairs with different spectrum availability and a new routing protocol has to be designed and adopted, enabling for route discovery capabilities, taking into account spectrum heterogeneity in different geographical locations. Route quality issues have also to be investigated since the actual topology of such multi-hop CR networks is highly influenced by primary users' behaviour, and classical ways of measuring/assessing the quality of end-to-end routes (nominal bandwidth, throughput, delay, energy efficiency and fairness) should be coupled with novel measures on path stability. Furthermore, route maintenance is a vital challenge considering the above mentioned scenario. The unpredictable appearance of a primary user at a specific time period is possible to make a given channel unusable at local level, thus resulting in unpredictable route failures, which may require frequent path rerouting either in terms of nodes or used channels. In a general context, routing in a TVWS based ad-hoc CR network constitutes a rather important but yet unexplored problem, especially when a multi-hop network architecture is considered. The design of a new routing protocol is therefore required, towards overcoming challenges defined above and establishing/maintaining optimal routing paths between secondary users with heterogeneous TVWS availability.

4.2.1. **Routing Protocol based on a Signalling Mechanism**

Towards enabling for efficient data transition between source and destination secondary nodes in the above mentioned scenario, a novel routing protocol was designed, implemented and evaluated under controlled simulation conditions. The proposed routing protocol is based on the exchange of AODV-style messages [98] between secondary users, including two major steps (route discovery and route reply). During the route discovery step, a RREQ (route request) message, including TVWS availability of nodes is sent by the source user to acquire a possible route up to the destination user. Once the destination user receives the RREQ message, it is fully aware about the spectrum availability along the route from the source user. The destination user then chooses the optimum routing path, according to a number of performance metrics (e.g. backoff delay, switching delay, queuing delay, number of hops, throughput) and assigns a channel to each secondary user along the route. It has to be noted here, that the evaluation of performance metrics is conducted, by each intermediate node during the routing path of the RREQ message. In the next step, destination user sends back a RREP (route reply) message to the source user that includes information regarding channel assignment so that each node along the route can adjust the channel allocation accordingly. Once this RREP is received by the source user, it initiates useful data transmission.

Fig. 4-2 presents the detailed process of the proposed routing protocol for handling both RREQ and RREP messages. The source user initiates a flow (i.e. New Flow in Fig. 4-2), transmitting a RREQ message to an intermediate node located in a neighbouring location.

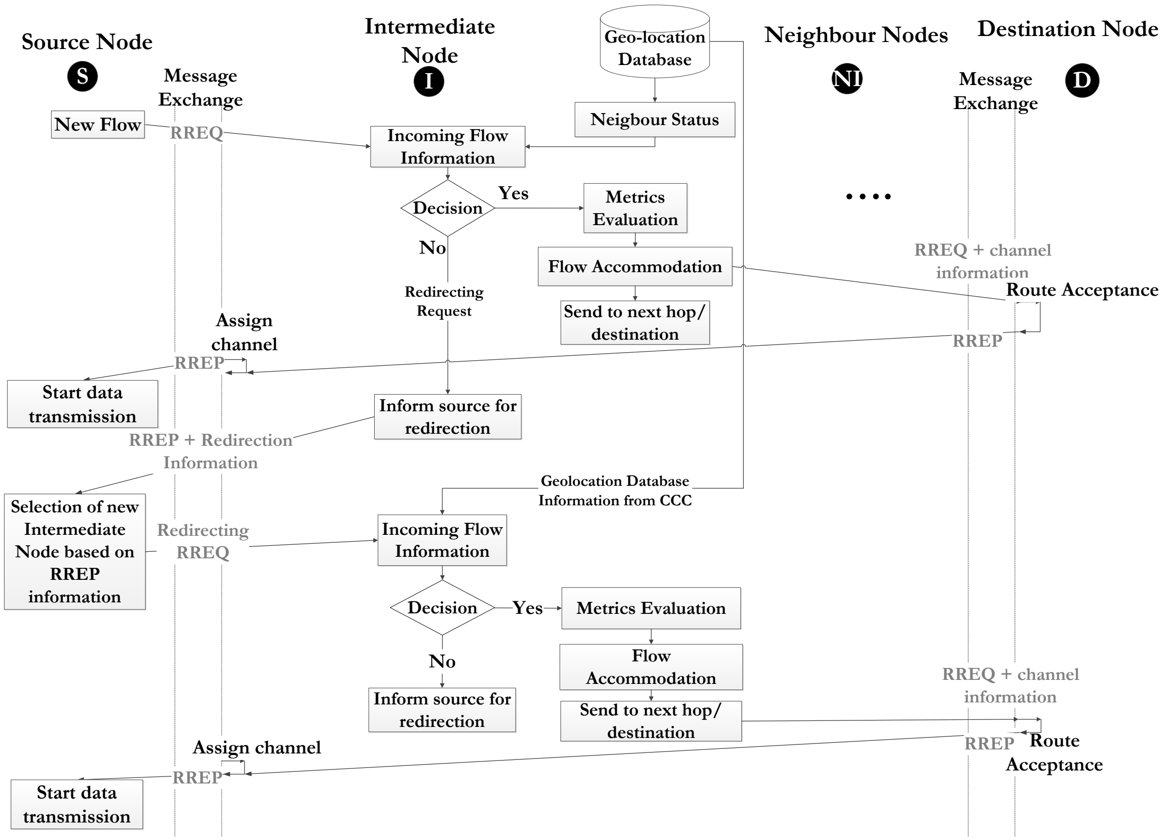

Fig. 4-2 Message exchange process of proposed routing protocol

The intermediate node is updated by Geo-location database about TVWS availability of its neighbouring nodes and determines if it is capable or not to accommodate the incoming flow from source user. If it is capable, it then evaluates the performance metrics, accommodates it and finally forwards it to the next hop or to the destination user, by forwarding the RREQ message. Once the destination user receives RREQ message, it is fully aware of channel availability along the route from the source node. Destination user sends then back a RREP message to the source user. This message contains information regarding channel assignment so that secondary users along the route can adjust the channel allocation accordingly. Once the source user receives the RREP, the routing path has been established and useful data transmission is initiated.

In the case when the intermediate node is not capable to accommodate the incoming flow (i.e. New Flow in Fig. 4-2), redirection process is in charge of informing the source user, about the neighbouring node, which could possibly act as an alternative intermediate node. In such a case, the intermediate node sends a RREP message to the source user, including redirection information. As soon as the source user receives this message, it broadcasts a redirecting RREQ message to the next possible intermediate node, which is then in charge to decide if it is feasible to accommodate the data flow, evaluate the performance metrics and forward it to the next hop. The proposed routing protocol determines a route only when a source user wishes to send a data flow to a destination user. Routes are maintained as long as they are needed by the source user and the exploitation of sequence numbers in the exchange messages guarantee a loop-free routing process. Furthermore, the proposed routing protocol as a reactive one, creates and maintains routes only if it is necessary, on a demand basis. The routes are maintained in routing tables, where each entry contains information, regarding destination user, next hop, number of hops, destination sequence number, active neighbouring nodes for this route and expiration time of the flow. The number of RREQ messages that a source user can send per second is limited, while each RREQ message carries a time to live (TTL) value that specifies the number of times this message should be re-broadcasted. This value is set to a predefined value at the first transmission and increased during retransmissions, which occur if no replies are received. The basic steps of the proposed message exchange process are summarized in the pseudocode of Table 1.

```
Initiate New Flow "f"
k = number of neighbour intermediate nodes
//Decision of node "n"
for (i=1; i++; i=k){
  Update Intermediate Node "n" with neighbour status
  If "n" have neighbours in the same TVWS
    then flow accommodation and flow evaluation E_f
//Flow redirection
 else do{
   generate and broadcast redirection information message
   flow accommodation and evaluation En_i
  until (receive route acceptance)
  generate and send RREP to source node
}
Start data transmission
```

Table 12 Basic steps pseudocode of the proposed message exchange process

4.2.2. Optimization of the Proposed Signalling Mechanism

The sub-section elaborates on the enhancement of the proposed routing protocol. More specifically, the assigning mechanism aims to alleviate the service load of intermediate nodes, so it is adapted to every intermediate node, which is further able to determine if a neighbour node performs better in the routing path. For this scope, the message exchange process of the proposed routing protocol has been modified (see Fig. 4-3), in order to consider the new feature of the assigning mechanism.

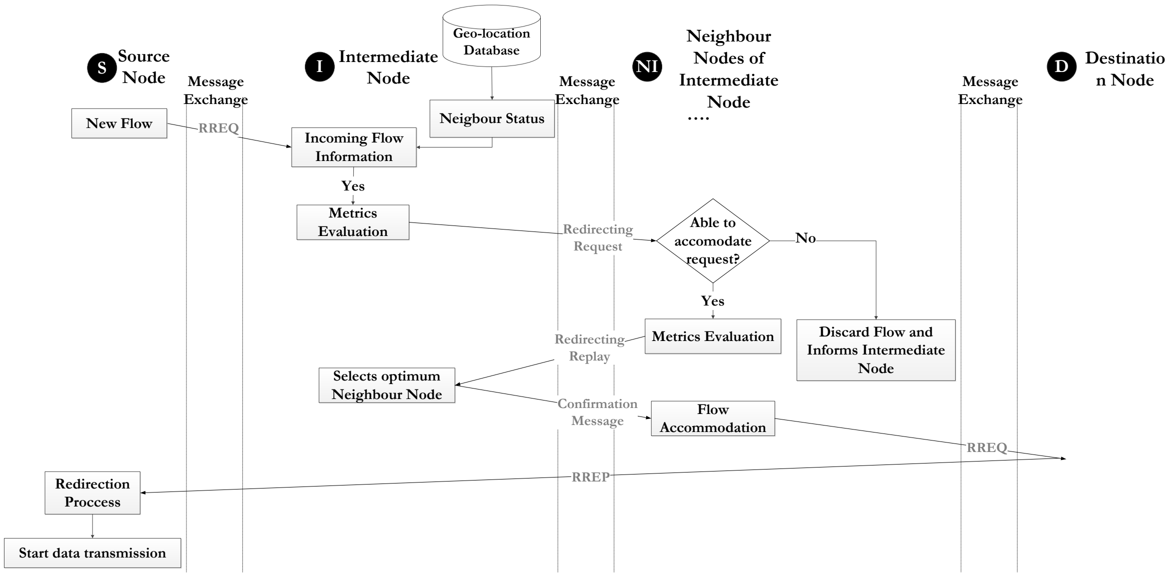

Fig. 4-3 Optimized message exchange process enhanced with assigning mechanism

When a source node initializes a new flow, by sending a RREQ, intermediate node is informed, regarding neighbourhood nodes status from the Geo-location database through the CCC. Then, the intermediate node evaluates the new flow (i.e. performance metrics) and encapsulates the evaluation result in a message, which is forwarded to all neighbouring nodes, instead of adopting the process proposed in the initial version of routing protocol. This message is the redirecting request signal in Fig. 4-3. Once the neighbouring nodes receive a redirecting request, they check its validity with the corresponding flow, ensuring that they are not the source/destination nodes or next-hop nodes of that flow. Then the neighbouring nodes initiate a process, in order to evaluate the flow and they send to the intermediate node the result of the evaluation through a redirecting replay message. Once the intermediate node receives the redirecting reply from several neighbouring nodes, it then selects the optimum one, in order to serve/accommodate the incoming flow. Finally, the intermediate node generates a RREP message, in order to inform the source node regarding the new candidate node and sends a confirmation message to the new intermediate node informing it to handle the flow. On the side of the source node, once RREP message is received, it changes the next-hop node and starts data transmission. Also, the enhanced routing protocol determines and maintains the routes only if it is necessary, on a demand basis, as long as a source node wishes to send a data flow to a destination node. Routing tables are used in order to maintain the possible routes, containing information, regarding destination user, next hop, number of hops, destination sequence number, active neighbouring nodes for this route and expiration time of the flow. In the same manner, as it was described in the initial version of the routing protocol, the number of RREQ messages carries a time to live (TTL) value that specifies the number of times this message should be re-broadcasted from source node to next hop. This value is set to a predefined value at the first transmission and increased during retransmissions, which occur if no replies are received. The basic steps of the proposed message exchange process can be summarized in the pseudocode of Table 2.

1: Initiate New Flow "f"

2: Update Intermediate Node "n" with neighbour status

3: Evaluation of flow E_f

```
4: k = number of neighbour intermediate nodes
//Decision of node "n"
5: for (i=1; i++; i=k){
6:  if i = sending node ||next-hop node || destination node
7:    then discard message
8:  else
9:       flow evaluation En_i
10:  if En_i > E_f
11:       then flow accommodation
  //Flow redirection
12:  else do
13:        generate and broadcast redirection information message
14:         flow evaluation En_i
15:         flow accommodation
16:  until (receive route acceptance)
17:  generate and send RREP to source node
18: }
19: Start data transmission
```

Table 13 Basic steps pseudocode of the proposed message exchange process with assigning mechanism

4.3. Performance Evaluation Analysis, Experimental Results and Discussion

Towards verifying the validity of the proposed routing protocol, several experimental tests were conducted, under controlled conditions (i.e. simulations). More specifically, in such scenario intermediate nodes are receiving concurrent data flows, stemming from other secondary users, resulting to increased delays. A number of data flows are contending to pass through the same intermediate node, thus evaluation of delays is crucial regarding the efficient performance of the proposed routing protocol. In this context, a number of delay metrics [66], [99], [100], [101] are evaluated, such as switching delay ($D_{switching}$), medium access delay ($D_{backoff}$) and queuing delay ($D_{queuing}$). Switching delay occurs when a secondary user during the routing path switches from one channel to another, while medium access delay, namely backoff delay, is based on the MAC access schemes used in a given frequency band. Backoff delay is defined as the time from the moment that a data flow is ready to be transmitted up to the moment the data transmission is successfully initiated. Queuing Delay is based on the output transmission capacity of a secondary user on a given channel. More specifically, queuing delay represents the time needed for a data flow to wait in a queue until it can be processed. Next subchapters elaborate on the performance evaluation of proposed routing protocol, as well as on a quantitative and qualitative comparison among both versions of it.

4.3.1. Performance Evaluation of Initial Routing Protocol

Towards evaluating the performance of the proposed routing protocol, a simulation scenario was designed and developed (see Fig. 4-4), where secondary users are scattered in three geographical areas (i.e. A, B and C in Fig. 4-4) with different TVWS availability. Secondary users located in the first geographical area opportunistically operate using channels from 52 up to 60, while remaining channels are dedicated for usage by primary users. Also, secondary users located in the second and third geographical areas are able to transmit on channels 41-47 and 49-60, respectively. In this simulation scenario, secondary users located outside these areas, are able to operate on all the available channels (i.e. channels 40-60) and act as coordinator nodes (intermediate secondary nodes in Fig. 4-4). These nodes are enhanced with a coordination mechanism that enables to determine routing paths between secondary users with different TVWS availability in areas A, B and C. Coordination nodes have sensing capability and are connected with a Geo-location database that includes TVWS availability for all geographical locations. The main purpose of the Geo-location database is to enable the protection of the primary users, located inside geographical areas A, B and C, from harmful interference caused, by secondary users operating in TVWS. Towards enabling for a sufficient protection, various parameters have to be specified in conjunction with the overall anti-interference database design. The database specifications follow the current approach of unlicensed use of TVWS, addressed by regulators, such as FCC, OFCOM and CEPT. Besides the information on the primary users that the database holds, it also includes the Geo-location information per geographic pixel for a specific region and records of the secondary nodes that operate in the specific region. It has to be noted here that secondary nodes located in geographical areas A, B, C, regularly update in real-time the Geo-location database regarding the TVWS channels occupied by them, through the intermediate nodes (i.e. intermediate nodes communicate with Geo-location database in CCC 40, see Fig. 4-4). Due to the vast amount of information that the database is expected to store, a hybrid approach for its topology design is required. Therefore, for efficiency and better performance, Geo-location database adapts a two level topology. The first level contains regulator controlled information, which includes the primary users' parameters. This information can be contained in one database that holds information per region inside a large geographical area (national level). The second level of information holds the calculated Geo-location information and the operating secondary nodes devices per specified region of control. This design also offers the flexibility of the deployment of more than one database for one region and thus allows competitive operation of database administrators.

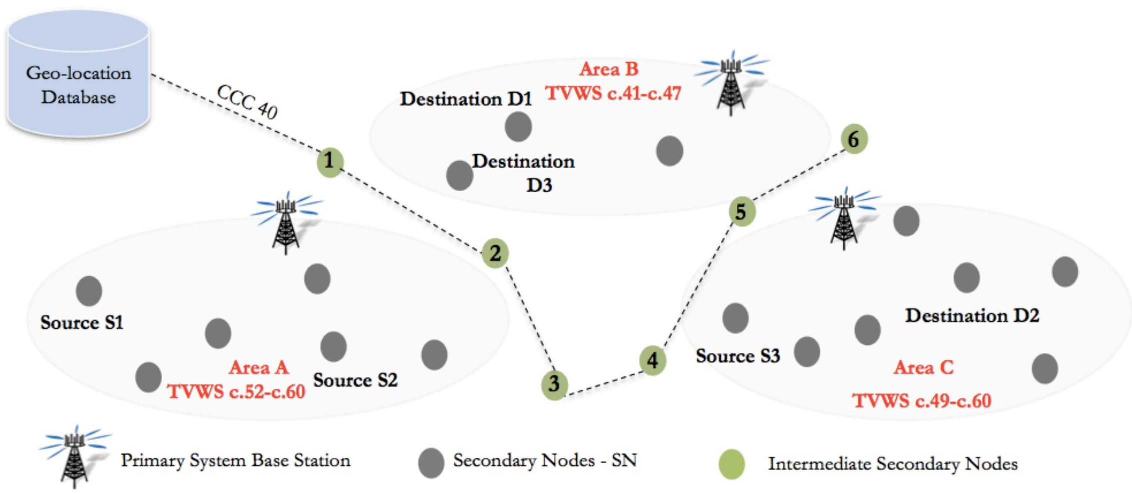

Fig. 4-4 Simulation scenario based on ad-hoc communication of secondary nodes

Moreover and according to the simulation scenario a queuing system was set up, in order to evaluate the nodes queue, exploiting a M/M/1/K Kendall model [102], utilising an inter-arrival time (i.e. first M of the M/M/1/K model), as well as an accommodation/serving time (i.e. second M of the M/M/1/K model) following exponential distributions based on the load/service rate (i.e. ρ). The system capacity (or number of flows can be served) was set to K = 1, while the service rate ρ depends on the parameters λ and μ. The number of data flows arriving every second denotes as λ, while μ denotes the number of data flows that are accommodated every second. Load/service rate is equal to λ/μ and during the simulation test load was varied from 0.05 to 0.45, towards evaluating the node queue under different loads [103]. The formulation of mean queuing delay $D_{queuing}$ and losses rate P_{block} [104], [105] are depicted below:

$$D_{queuing} = \frac{\rho}{\mu - \lambda}$$

Equation 4-1

$$P_{block} = \frac{(1-\rho)\rho^{k}}{1-\rho^{k-1}}$$

Equation 4-2

Additionally, the evaluation of $D_{switching}$ and $D_{backoff}$ [66], [100] is crucial in such simulation scenario. Then, cumulative delay at an intermediate node i is based on them and is computed as follows:

$$Node\ Delay = \sum_{1}^{i}(D_{switching} + D_{backoff})$$

Equation 4-3

Finally, end-to-end delay from the source user up to the destination one is computed as the overall sum of $D_{queuing}$ and ND:

$$D_{End-to-End} = D_{queuing} + Node\ Delay$$

Equation 4-4

Based on the metrics defined above the performance evaluation results below represent losses rate (see Fig. 4-5) and mean queuing delay (see Fig. 4-6), for differed service rate values (i.e. load). It can be observed that both losses rate and queuing delay are increasing when service rate is varied from 0.05 up to 0.45, validating the proper operation of intermediate nodes buffers when the M/M/1/K Kendall model is adopted.

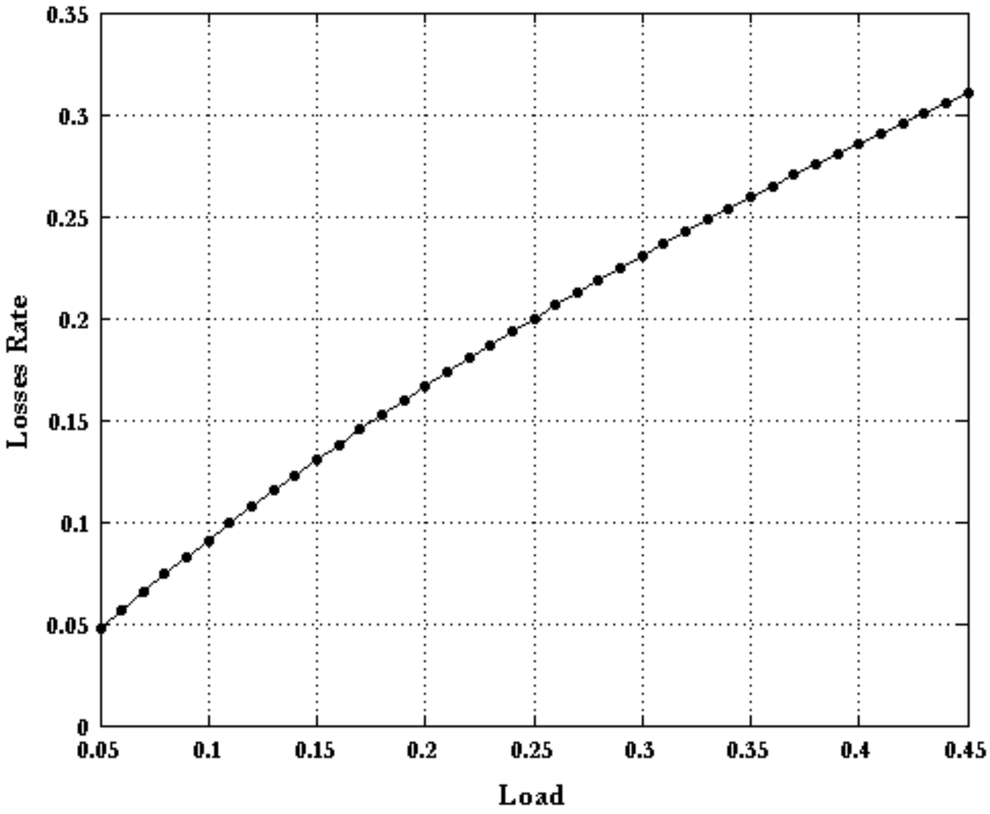

Fig. 4-5 Losses Rate in nodes queues

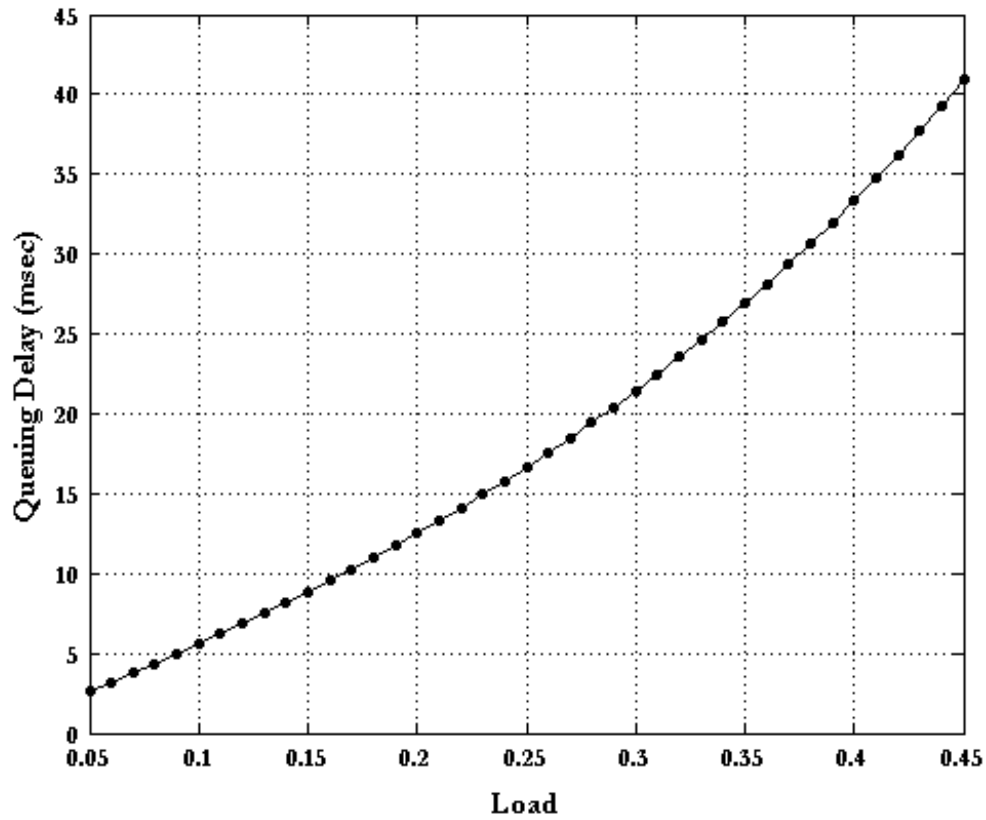

Fig. 4-6 Queuing Delay in nodes queues

This simulation scenario includes three source secondary users (i.e. S1, S2 and S3 users in Fig. 4-7) that wish to deliver data flows to corresponding destination secondary users (i.e. D1, D2 and D3 users in Fig. 4-7) located in geographical areas with heterogeneous TVWS availability. The main challenge in such an ad-hoc CR network architecture is the spectrum heterogeneity of the available TVWS between neighbouring areas, prohibiting secondary users to communicate since there is no CCC. In such a case, coordination nodes will act as intermediate/bridge nodes between source and destination secondary users, coordinating data flows and deciding the most optimum routing path that has to be followed. According to the simulation scenario depicted in Fig. 4-7, when secondary user S1 wishes to transmit data flows to secondary user D1, it firstly communicates with coordination node 2 on channel 52, which is in charge to route data flows to D1 by switching to channel 43. Additionally, secondary user S2 wishes, at the same time to transmit data flows to secondary user D2 (see Fig. 4-7). In this case, coordinator node 3 located between geographical areas B and C is not able to process data flows from S2, since it serves at the same time data flows originated from secondary user S3 targeted to secondary user D3. In such a case, data flows are redirected to coordination node 2, which is then in charge to communicate with D2 on channel 60. It has to be noted here that all coordination nodes are connected to a TVWS Geo-location database, through a CCC (i.e. channel 40).

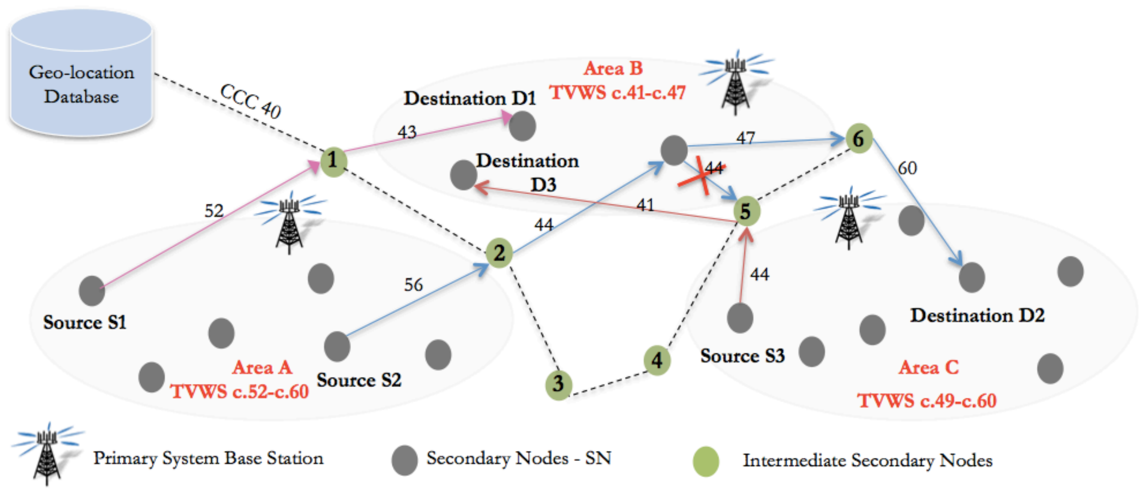

Fig. 4-7 Routing paths obtained by simulation scenario

Based on the metrics defined above performance evaluation results of Fig. 4-8) represent end-to-end delay and node delay for all three data flows of the simulation scenario defined above. The simulation results that were obtained, provided the routing paths for S1-D1, S2-D2 and S3-D3 communication (see Fig. 4-7). In this context, Fig. 4-8 represents end-to-end delay and node delay for three different data flows of the routing paths obtained above (see Fig. 4-7). It can be observed that end-to-end delay and node delay for data flow 2 is higher in comparison to delays of data flows 1 and 3, since the routing path from S2 secondary user to D2 secondary user (see Fig. 4-8), includes a higher number of hops, as well as a redirection process is occurred.

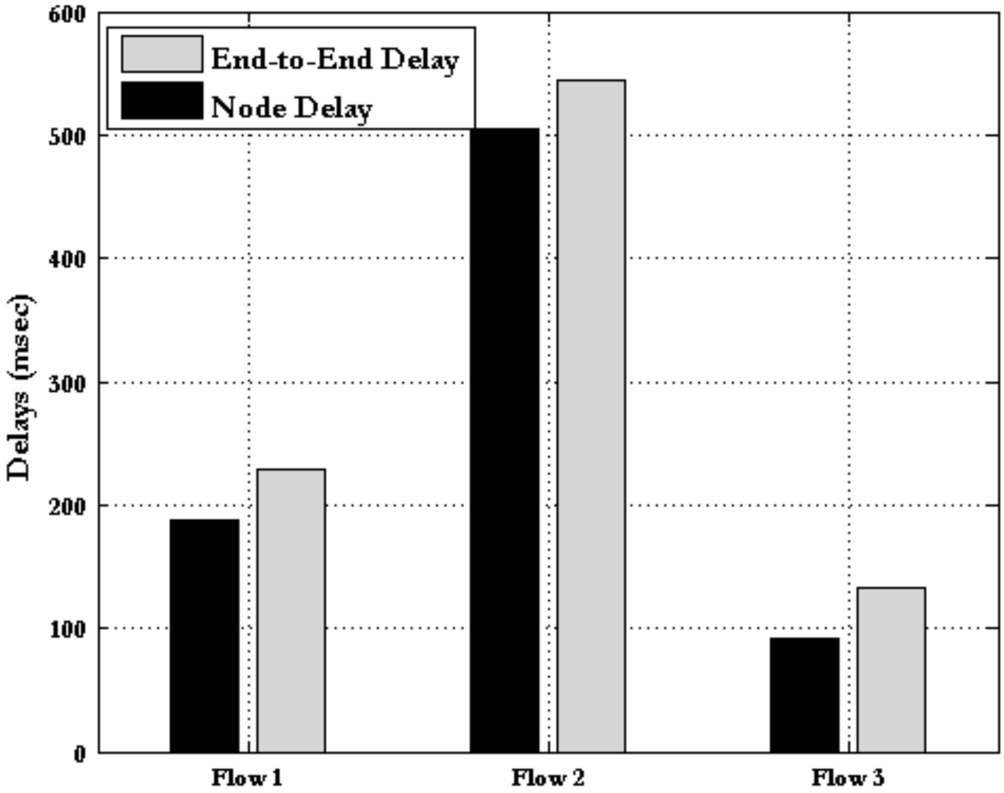

Fig. 4-8 End-to-End Delay and Node Delay of data flows

Towards further evaluating the performance of the proposed routing protocol, a discrete time Markov chain process is adopted. The number of active nodes at a given time is defined as the initial state of the system. This number represents the discrete time states of Markov chain, given by a random variable Xt{0,1,2,…,M}. Also, it is assumed that a finite number of M nodes is connected to the coordination node that utilizes the proposed routing protocol. Each secondary node is equipped with a buffer with capacity of a packet. The discrete time is a step in the transition of Markov model analysis. Each secondary node generates packets at the beginning of every timeslot (i.e. per sec) independently of the other nodes with probability of arrival Pa, following independent geometric distribution. In case of unsuccessful transmission (i.e. collision), the packet enters the buffer of the node and is marked as active (i.e. backlogged), while nodes with empty buffer are marked as free (i.e. unbacklogged). Moreover, each secondary node attempts to retransmit a packet with probability Pr, independently from other ones at the beginning of every timeslot (i.e. per sec).

Based on the assumptions defined above, the performance evaluation results (see Fig. 4-9, Fig. 4-10) represent a) the percentage of time that a node is occupied/active with a successful transmission of packets and b) the mean delay that is required in order for a packet to be transmitted. In more detail, Fig. 4-9 depicts the percentage of time that a node is occupied with a successful transmission of packets over the probability Pa that a node generates a packet. According to the results, it is observed that for low values of Pa the successful transmission of the packets is 37%, while for Pa from 0.04 to 0.3, it is observed a rapidly decrease of the successful transmission, which continues to decrease at a slower rate. As far as the probability increases, the number of conflicts/collisions is getting higher.

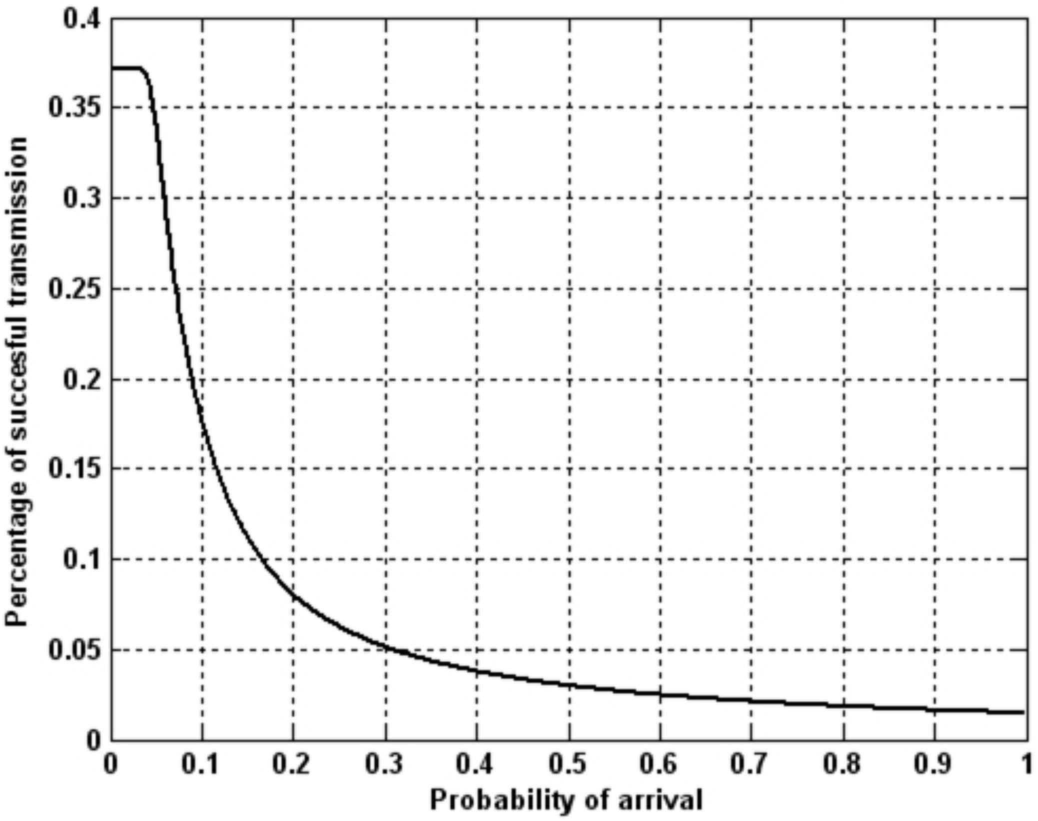

Fig. 4-9 Percentage of a successful transmission

Fig. 4-10 represents the mean delay that is required in order for a packet to be transmitted. During the initial values of Pa (i.e. up to 0.04), the mean delay is relatively constant due to the maximum percentage of successful packet transmission (see initial values of percentage of successful probability in Fig. 4-9). Then, a steady increase is observed, which is normal since as the probability of each packet to be transmitted is increased, the number of active nodes will be higher in order to send a packet without a collision. Finally, Fig. 4-11 represents mean delay over percentage of successful transmission of packets. It is observed that as the percentage of successful transmission increases, the mean delay decreases. This is also verified in Figures Fig. 4-9 and Fig. 4-10.

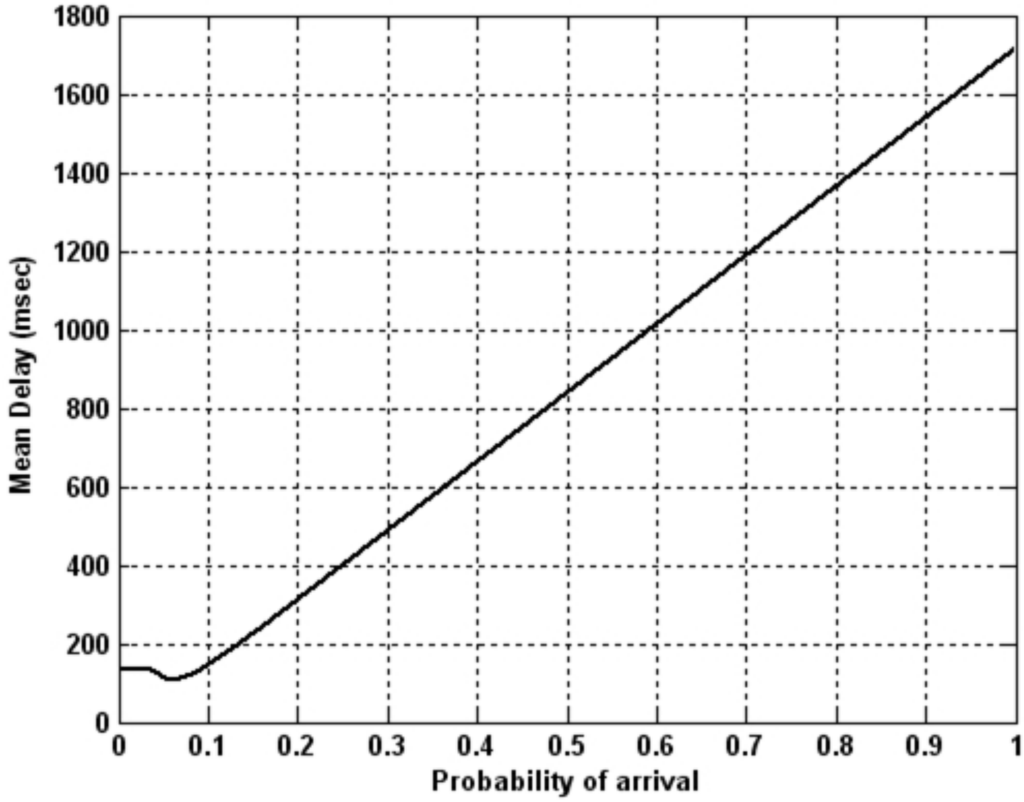

Fig. 4-10 Mean delay for packet transmission

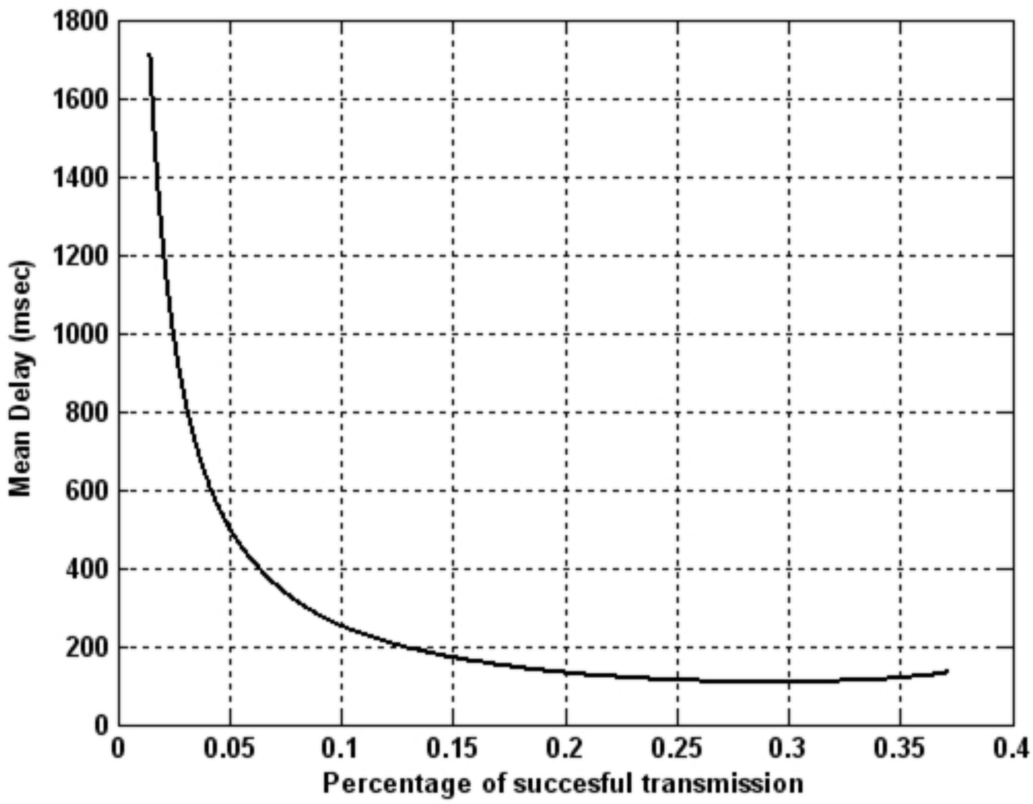

Fig. 4-11 Mean delay over successful transmission

4.3.2. **Quantitative and Qualitative Comparison of both routing protocols**

Fig. 4-12 depicts an urban area of Munich City in Germany (2.2Km x 2.2Km), where secondary nodes are scattered with different TVWS availability, based on measurements performed in [106] populating Geo-location database. Secondary nodes located in this geographical area opportunistically operate, using vacant TV channels, while the remaining channels are dedicated for usage by primary nodes. In this simulation scenario, all secondary nodes (i.e. wireless mesh routers) are possible to act as intermediate secondary nodes in Fig. 4-12. These mesh network nodes are enhanced with an assigning mechanism that enables to determine routing paths between secondary nodes with different TVWS availability in such specific area. Assigning mesh nodes have sensing capabilities and are connected with a Geo-location database that includes TVWS availability for all geographical locations. The Geo-location database also provides to the intermediate communication nodes, data regarding the maximum allowable transmission power that can be used so that no causing interference to primary systems. For this reason, an initial study was conducted, in order to compute the transmission power limitations of communications nodes for each TVWS channel. Such an investigation was finalized in the framework of COGEU-ICT project [106] for the region of Bavaria in Germany. The main challenge in such an ad-hoc CR network architecture is the spectrum heterogeneity of the available TVWS between neighbouring areas, prohibiting secondary nodes to communicate continually, since the spectrum is opportunistically exploited. In such a case, assigning nodes act as intermediate/bridge nodes between source and destination secondary nodes, coordinating data flows and deciding the most optimum routing path that has to be followed.

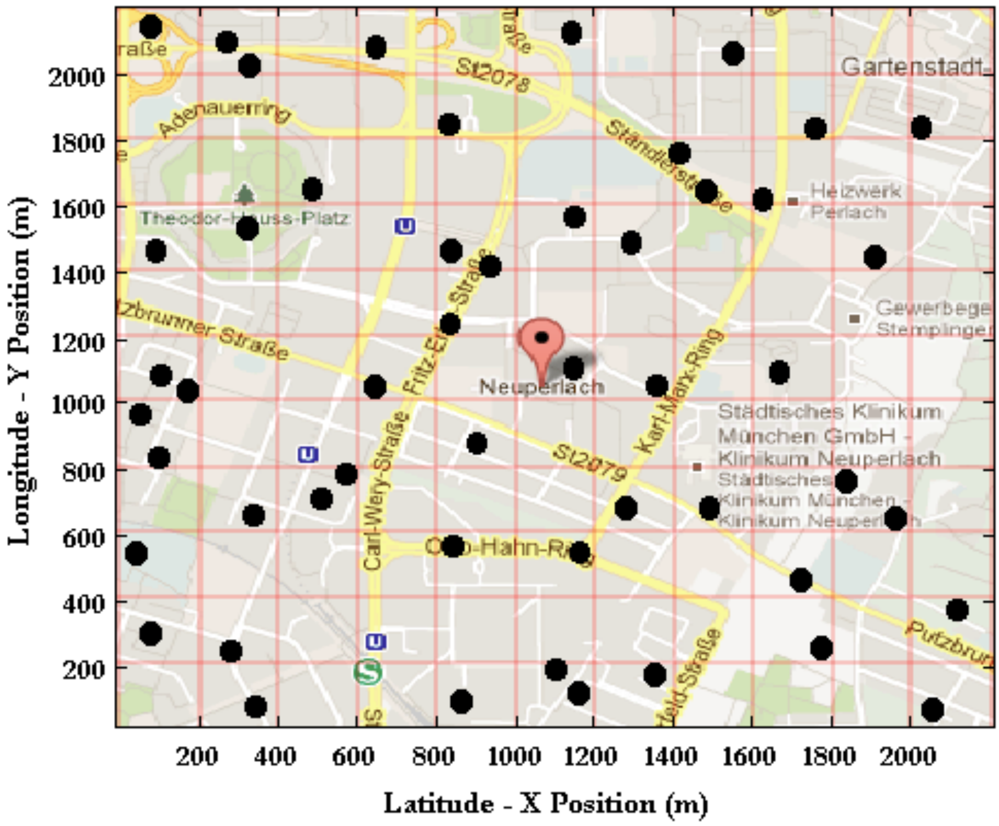

Fig. 4-12 Munich urban-area with network nodes operating over TVWS

More specifically, simulation results below compare the performance of the initial version of the proposed routing protocol presented in sub-chapter 4.2.1, with the enhanced one in sub-chapter 4.2.2, by implementing an assigning mechanism that mitigates the service load of intermediate nodes, resulting a routing path that performs better compared to other paths. Delays of both versions of the protocol were compared based on the number of active flows in the simulation area, the activation probability of an idle Primary System, as well as the distance of the CR source and destination nodes that wish to communicate.

In the area of Munich, the available TVWS, based on Geo-location database [107], varies from 1 to 3 and create inconsistency of spectrum opportunities among secondary nodes. More specifically the available TVWS in this location are 57, 59 and 60 channels. Also, in this area there are more vacant TVWS, but the maximum available transmission power is too low for a secondary system to operate. Experimental simulations were conducted to quantify the performance of both the proposed versions of routing protocol. Up to 50 secondary nodes are randomly distributed over a 2200 m by 2200 m area. The evaluation topology is shown in Fig. 4-13, where the source nodes are on the top and the destination is on bottom. Pairs nodes from S1 – D1 (source node 1 – destination node 1) to S10 – D10 (source node 10 – destination node 10) represent the flows that are initiated in this simulation scenario, in order to evaluate the protocol under a heavy load.

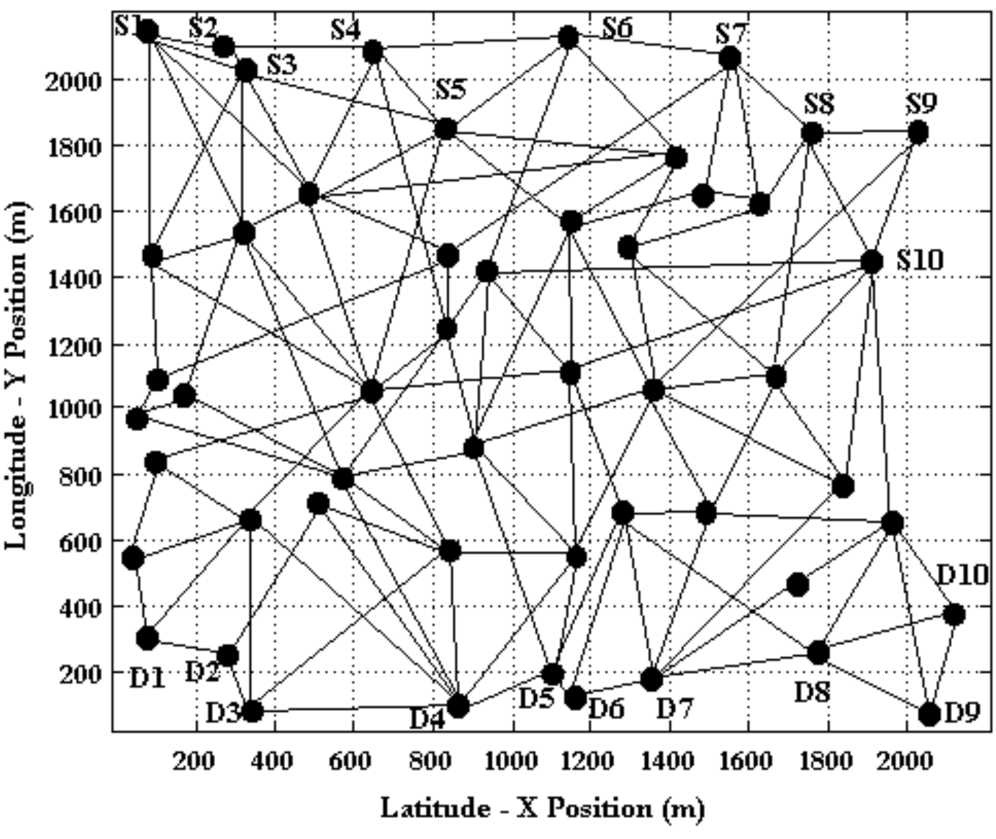

Fig. 4-13 Mesh network topology

Fig. 4-14 shows simulation results and performance comparison of mean End-to-End Delay, while the number of active flows is increasing. It is clear that when routing protocol incorporates the assigning mechanism, heavy service load is distributed around every intermediate node. It has to be noted here that when the number of active flows in the network is small, assigning mechanism does not show much advantage, since queuing system is just formed or the load is not heavy enough to launch the flow redirection. However, when the number of active flows exceeds 3, intermediate nodes begin to suffer the accumulating queue, and from then on the flow redirection become necessary. It is also observed that the mean End-to-End Delay is decreased, in case of the enhanced routing protocol, and the most preferable path van be established. Fig. 4-15 shows the simulation results of End-to-End Delay of one flow (i.e. 1st flow S1-D1) when the probability of primary user presence increases, while Fig. 4-16 presents the same metric, but in this case each point represents the average of End-to-End Delay for all flows (S1-D1 up to S10-D10) for a certain value of primary user presence probability.

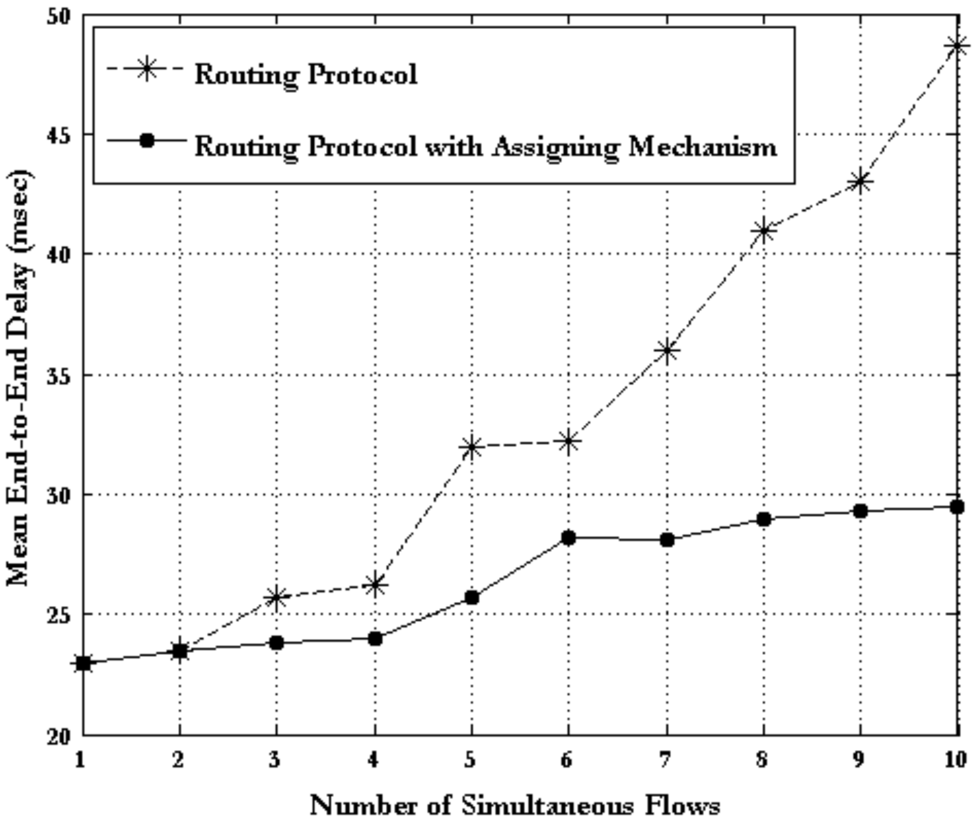

Fig. 4-14 Mean End-to-End Delay for different number of simultaneous flows

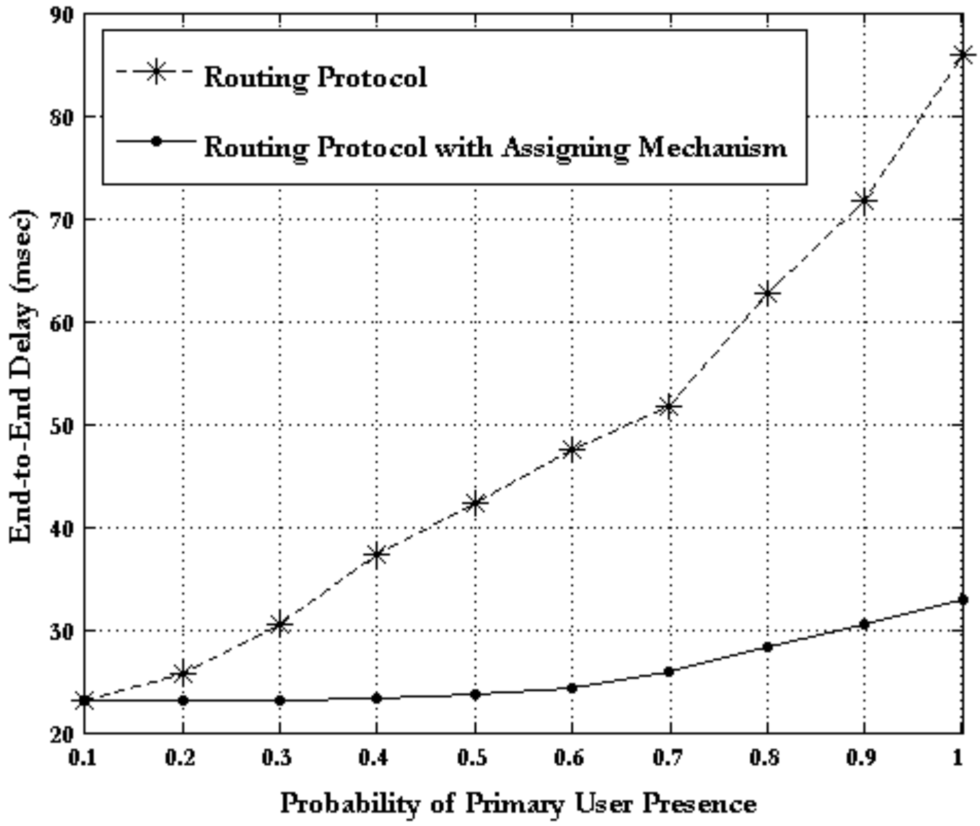

Fig. 4-15 End-to-End Delay for the 1st flow versus probability of PU presence

Both figures present that, as the probability of primary users presence is getting higher, the delay is increasing, while in the case of initial routing protocol the delay increase is more significant. This result is reasonable, since the probability of the presence of an incumbent system is detected as a route failure of the flow, introducing in this way additional delay. Moreover, it is observed that the probability of a primary system presence, affects significant routing procedure in this scenario, as the available TVWS are only 3. This makes difficult to obtain links between secondary intermediate nodes. Therefore, the possible routing paths are high, as the topology of the node is a mesh network, and the assigning mechanism of each node requires enough time to compute the delays of all possible routing paths.

Moreover, Fig. 4-17 presents the average End-to-End delay that occurred among the source and destination nodes as the distance between them is increased. From this figure it is clear that the distance affects the delay among nodes. This result is reasonable since the longer is the routing path, the more numerous are the primary nodes that affect the path, and the more significant are the effects of the route range/diversity. It is further observed that the initial version of the routing protocol adds higher delays as the distance is increasing rather than those occurred when assigning mechanism is introduced, resulting the most optimal routing path between the source and destination nodes. Consequently, the longer is the path, the more significant are the effects of the route diversity. Finally, Fig. 4-18 shows the comparison among both versions of routing protocol, under the number of hops that are required in order to make feasible all paths between the source and the destination nodes, for each flow set according to the simulation scenario. This comparison results that the assigning mechanism performs better, as the second protocol makes the decision on every hop instead of the process adopted in the initial one.

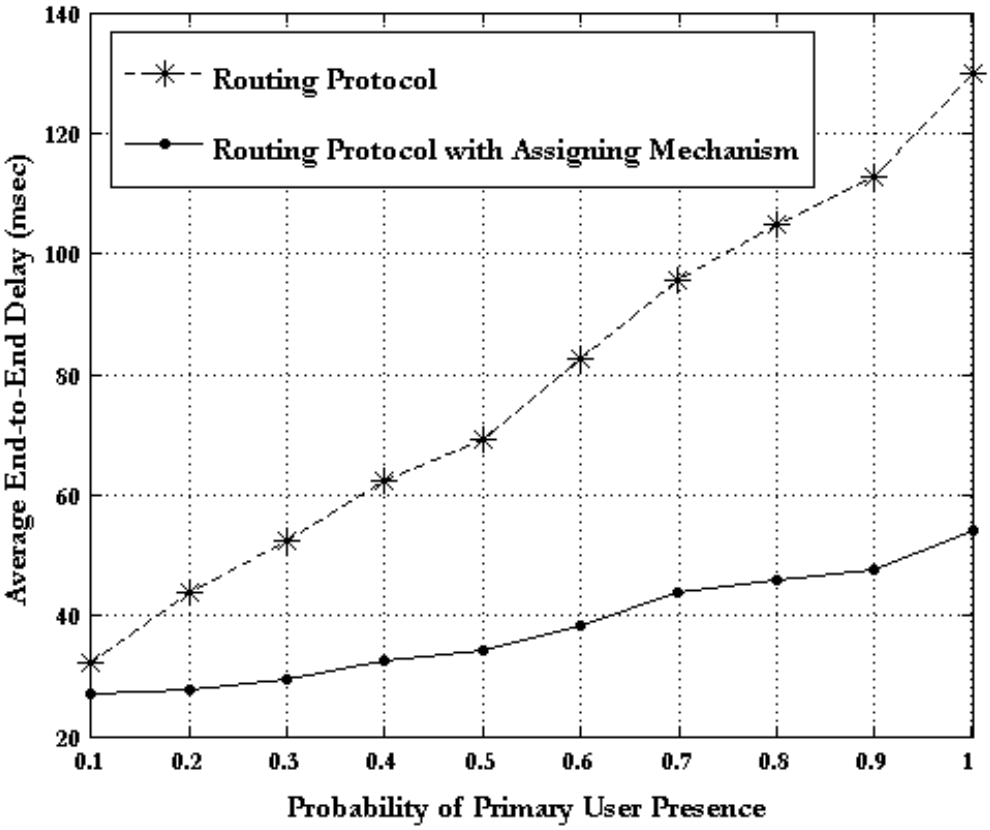

Fig. 4-16 Average End-to-End Delay for all flows versus probability of PU presence

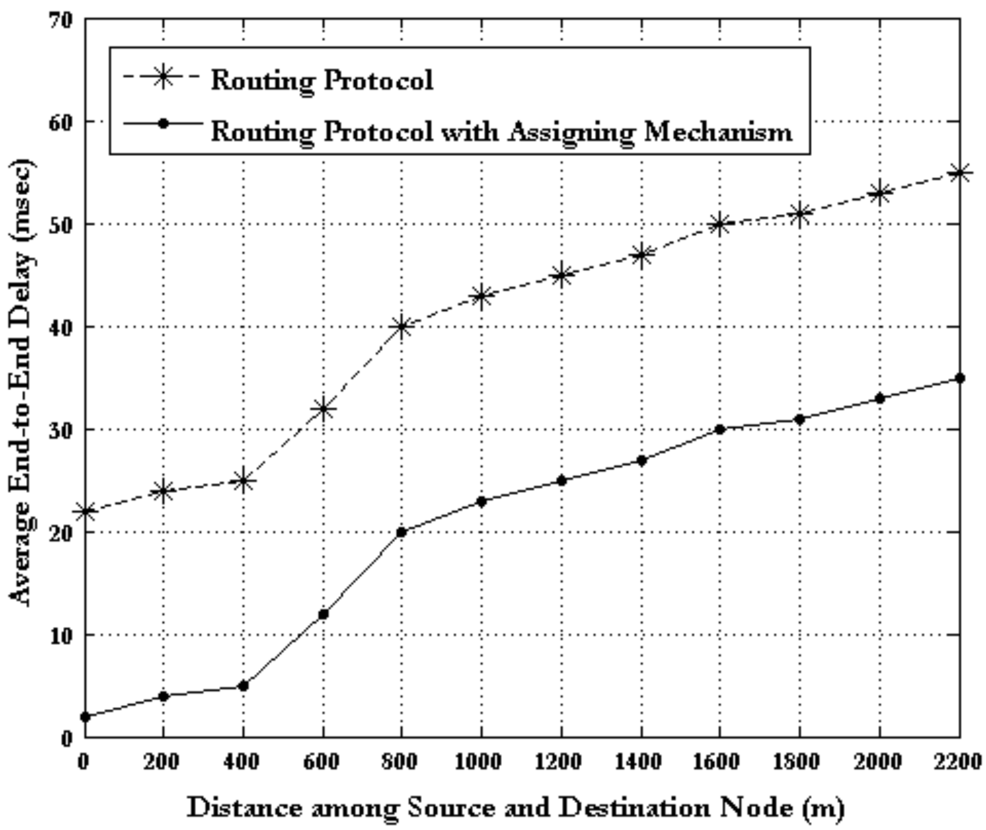

Fig. 4-17 Average End-to-End Delay versus node distance

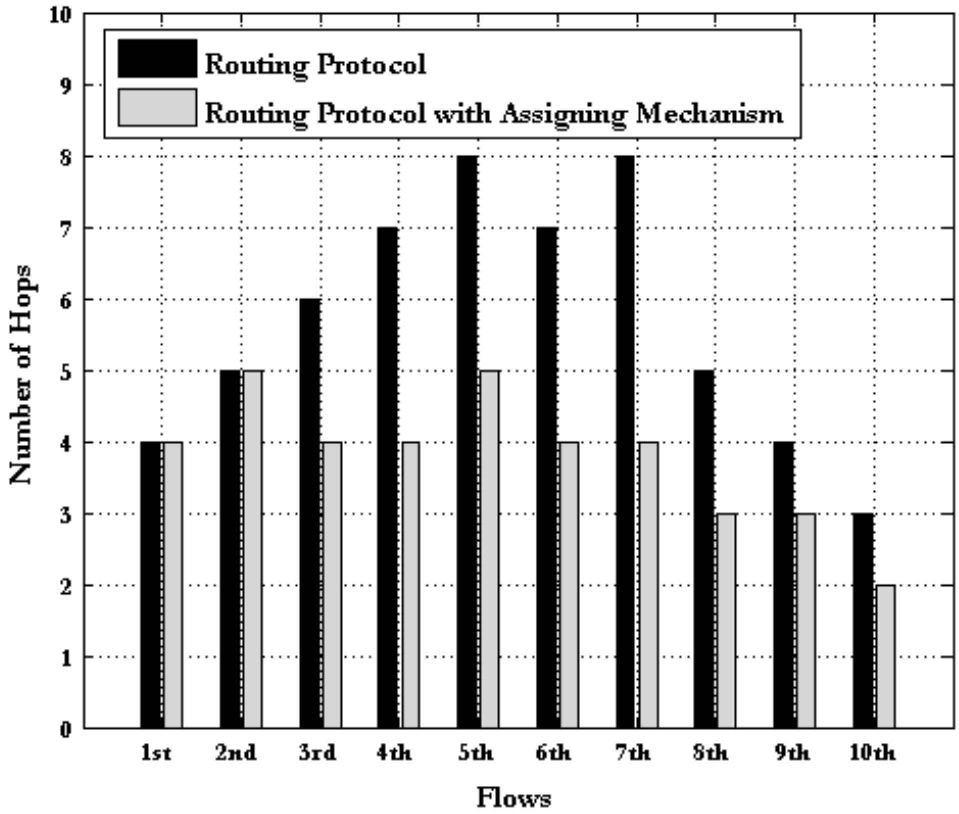

Fig. 4-18 Number of Hops per each flow

4.4. Summary

This chapter elaborated on the design and implementation of a novel routing protocol that contributed to the issue of spectrum heterogeneity among different geographical areas, in a cognitive radio network infrastructure, by exploiting an assigning mechanism to obtain hop-by-hop optimal paths, while reliable data flow among secondary communication nodes was enabled. The proposed routing protocol established an End-to-End optimal path, whereas secondary nodes in the CR network could efficiently and, in a collaborative manner, share requested data/resources. Performance evaluation through simulations proved that the proposed routing protocol in collaboration with the assigning mechanism, efficiently coordinated data transfer among secondary communication nodes, operating over TVWS based on Spectrum of Commons policy. In this context, a number of experimental tests was conducted under controlled simulation conditions, where various secondary systems were concurrently/simultaneously communicating in ad-hoc connections, accessing the available TVWS. The obtained experimental results verified the validity of the proposed routing protocol, towards enabling for an efficient inter-system operation between secondary nodes located in areas with different TVWS availability.

Part of the work presented in this chapter was published in [108], [109], [110], [111].

5. CONCLUSIONS

5.1. Overview

This final chapter of the thesis concludes it by resuming the research efforts, its scientific results and contribution to knowledge, as well as by identifying fields for future exploitation. In this context, section 5.2 summarises the work carried-out towards the design, implementation and performance evaluation of the proposed hybrid CR network architecture and relevant mechanisms, providing efficient TVWS exploitation based on both RTSSM and Spectrum of Commons policies. Section 5.3 elaborates on issues for future research based on the work carried out within the framework of this PhD thesis.

5.2. Innovation and Contribution to the State-of-the-art

This Ph.D. thesis presented the study, design and implementation of a hybrid cognitive radio system architecture and the corresponding data-link layer mechanisms (i.e. RRM), as well as the appropriate network-layer mechanisms (i.e. routing protocols) for intra- and inter-system communication, even among CR devices, located over highly heterogeneous/dispersed TVWS allotments. More specifically, it described a centralised cognitive radio network, where dynamic TVWS allocation among various secondary systems was coordinated by a spectrum broker, following the RTSSM policy, while intra-system radio resource management was based on the Spectrum of Commons model (ad-hoc deployment of CR devices). The spectrum broker administrated the economics of TVWS leasing, either via fixed-price or auction-based transactions. For efficient system performance, as a matter of maximum-possible radio resource exploitation and/or trading revenue, the thesis elaborated on the design and implementation of a prototype RRM and Trading framework at the spectrum broker side, in order to optimally orchestrate TVWS access. Towards this, a RRM algorithm was designed, developed and incorporated in the proposed centralized CR networking architecture, enabling for efficient TVWS exploitation, providing QoS to secondary systems, while either minimizing spectrum fragmentation or maximizing spectrum broker profit. Experimental tests verified the capacity of this novel algorithm to optimally allocate TVWS among secondary systems exploiting the proposed architecture, as well as to respect and fulfil certain QoS requirements.

More specifically, chapter 1 elaborated on emerging CR network infrastructures that were researched and developed in response to the current wireless networks needs for increased spectrum availability and better exploitation of the available radio resources. Deployment of CR networks satisfied the increasing users' demand for bandwidth-hungry, QoS-sensitive services, by enabling dynamic access to the available spectrum pool, along with on-demand utilization of radio resources. In this framework, this chapter reviewed the state-of-the-art concerning CR network architectures, configurations and potential policies for introducing them in licensed bands (i.e. TVWS), while elaborated on a number of technological challenges that provide for efficient exploitation of the available radio resources (i.e. RRM at the data-link layer), as well for optimum communication and efficient data routing among secondary users (i.e. routing protocols at the network layer).

In addition, chapter 2 elaborated on the proposed prototype hybrid system architecture and the corresponding data-link layer mechanisms. A centralized cognitive radio network was described, where the inter-system communication, in terms of dynamic TVWS allocation among various secondary systems, was coordinated by a spectrum broker, following the Real-time Secondary Spectrum Markets (RTSSM) policy. The spectrum broker optimally administrated the available resources interconnected with a Geo-location spectrum database, which was utilized to provide information for primary system protection. It also managed the economics of TVWS leasing either via fixed-price or auction-based transactions. The proposed research approach, incorporating a spectrum broker in the system architecture, minimized the probability of primary systems to become "selfish", overcharging the available radio spectrum, while spectrum broker also guaranteed QoS during TVWS allocation process.

Chapter 3 elaborated on the implementation of a simulation scenario that conformed to the design specifications, towards verifying the validity of the proposed CR network architecture based on RTSSM policy, via a series of preliminary performance experiments. In this context, it presented the implementation of a Radio Resource Management and Trading framework as a process for the inter-system operation that enables for the opportunistic trading of un-used TVWS, by secondary systems (i.e. cellular/wireless network providers), respecting several constrains and guaranteeing QoS related requirements, like restrictions associated with maximum transmission power thresholds and possible interference. Towards addressing such challenges, TVWS leasing methods were anticipated, functioning into the central networking unit, namely spectrum broker. This unit operated by optimally assigning radio spectrum resources to secondary systems in specific geographical locations, according to a combinatorial auction-based process. In this context, a number of preliminary experiments were designed and conducted under controlled conditions environment (i.e. simulation tests), elaborating on the overall system performance considering fixed-price and auction-based approaches. More specifically, and in the case of fixed-price, the experimental tests were conducted, in respect to spectrum fragmentation, spectrum utilization and simulation time. On the other hand, experimental tests, concerning auctions were conducted, in respect to spectrum broker benefit/utility, spectrum fragmentation, spectrum utilization and probability of accessing TVWS. Analysis of the experimental results, verified the validity of the proposed architecture in efficient spectrum allocation, fare and competitive sharing, establishing it as an alternative/complementary solution when extra spectrum is required to support high traffic.

Finally, chapter 4 focused on the study, development and experimental evaluation of a novel routing protocol (i.e. network-layer process), allowing communication among ad-hoc secondary users (i.e. CR devices). The proposed routing scheme was designed for ad-hoc CR constellations, where each communicating party was placed at different/isolated TVWS allotments, i.e. no direct communication link exists between the corresponding CR users. For these reasons, the proposed routing protocol encompassed mechanisms that took into account the system topology (in an end-to-end approach) prior to establish the best routing path.

5.3. Fields for Future Research

The work carried out within this Ph.D. thesis resulted to a prototype hybrid network architecture that allows efficient Radio Resource Management and TVWS exploitation, constituting the basis for the efficient and fast deployment/establishment of broadband metropolitan infrastructures. Prior to these, however, a number of issues have to be taken into account and confronted, ranging from data-link layer up to transport layer. More specifically, a potential field for future exploitation is the issue of energy efficiency in centralized cognitive radio network architectures. Measuring network lifetime is a critical design issue for uninterrupted information flow in CR networking architectures. CR networking nodes are energy 'hungry', operating on limited energy resources, whereas replacement or recharging of CR mobile terminals/devices is infeasible. Moreover, the fact that mobile devices change in time their location, there is no guaranteed QoS level during the resource exchange process, resulting to reduced performance responsiveness, under such conditions. Energy harvesting is important to be performed in CR networking systems, where network partition can frequently occur, since nodes move freely. This partitioning problem causes a part of data to be often inaccessible to a number of CR nodes. In turn, the energy consumed, by wireless devices, as well as the bandwidth allocation policy in collaboration with the power and frequency bandwidth measurements, pose a great challenge for both operators and wireless access technology planning developers, towards further exploiting the cooperative diversity and meeting QoS requirements of each service provided. As energy conservation is an important trade-off for high performance deployment in CR networks, the supporting energy schemes have to be reactive so that the energy levels of wireless nodes will be tuned, according to the associated parameters (i.e. capacity, traffic [112], [113] and remaining supporting energy of the nodes). In a general context, an energy-efficient scheme has to take into consideration the bounded end-to-end delays of transmission and provide connectivity assurance, by exploiting technical measurements of the network lifetime that are closely related to the transmission characteristics [114] and the underlying access policy used [87]. An efficient methodology should combine the temporal bandwidth-aware behaviour of the node with the access policy used for achieving optimal energy in an end-to-end path, using both mobile peer-exchange mode and radio access mode. Preliminary research work of the above-mentioned issue, has been submitted for possible publication in [117], [118].

Another potential field for future exploitation that arises from the conducted research is the issue of energy conservation in ad-hoc routing protocols. More specifically, Energy conservation figures an important aspect for the high performance deployment in ad-hoc CR networks. On one hand, the Energy Conservation scheme has to be reactive so that the energy levels of wireless nodes will be tuned, according to the estimated parameters (i.e. capacity, traffic [119] of the nodes). On the other hand, an energy-efficient scheme has to take into consideration the bounded end-to-end delays of the transmissions. As the network lifetime is closely related to the transmission characteristics [120] of a source node to a destination node and the underlying routing protocol used [121], a mechanism that combines the temporal traffic-aware behaviour of the node [113] and the efficient routing scheme in an end-to-end path has to be investigated. In [120], sleep-proxy nodes evaluate the duration of the activity periods of each node, according to the capacity and the estimated inter-cluster overall energy consumed within a time frame. Towards further investigating related schemes, fields for further research include the exploitation of traffic model and the characteristics of the volume of the traffic for a specified time window frame to CR systems, supported by the Backward Traffic Difference estimation. In order to minimize the energy consumption the Backward Traffic Difference measures the volume of the incoming Traffic that is destined for each one of the nodes within a time window frame. The Backward Traffic Difference [112], [113] has to take into consideration the repetition of the Traffic and estimates the Backward Difference for extracting the time duration for which the node is allowed to Sleep. In addition, the routing mechanism proposed in this Ph.D. Thesis, has to be strictly associated with the Energy-efficiency when the CR networking architecture hosts wireless nodes requesting spectrum, via which the traffic will be transferred. Therefore, the routing mechanism in collaboration with an energy-efficient scheme should guarantee the end-to-end availability of requested resources, whereas it should be able to significantly reduce the Energy Consumption. In addition, the mechanism should be able to maintain the requested scheduled transfers and the entire end-to-end connectivity. Many recent measurement studies [112] have convincingly demonstrated the impact of Traffic on the end-to-end connectivity [122], and thus showed the impact on the Sleep-time duration and the Energy Consumption. Measures extracted in real-time using realistic traffic [112], [122] have shown that the impact of the responsiveness of the routing scheme in regards to the end-to-end transmission reliability is significant. Real-Time communication networks and multimedia systems, exhibit noticeable burstiness over a number of time scales [123], [124]. Based on the stochastic traffic modelling, the traffic in most of the cases can be expressed in time exhibiting fractal-like characteristics [126]. The problem of hosting a scheme where, in collaboration with the routing mechanism used, takes into account the traffic characteristics in order to conserve energy has not yet explored. The scheme will be able to tune the wireless interfaces of the nodes to the Sleep or Active state according to the incoming Traffic and a model which considers the next Sleep-time duration. Notwithstanding, many Sleep-time scheduling strategies were introduced that model the node transition between ON and OFF states. Existing scheduling strategies for wireless nodes could be classified into three categories: the coordinated sleeping [125], where nodes adjust their sleeping schedules, the random sleeping [126], where there is no certain adjustment mechanism between the nodes in the sleeping schedule with all the pros and cons [113], and on-demand adaptive mechanisms [127], where nodes enter into Sleep-state depending on the environment requirements whereas an out-band signalling is used to notify a specific node to go to sleep in an on-demand manner. Although there are many schemes developed addressing different Energy conservation methodologies, the combination of a traffic-aware scheduling scheme with the routing protocol supported by the CR networking architecture, has not yet been explored. The latter poses a fertile ground for the development of new approaches with the association of different parameters of the communication mechanisms, in order to reduce the Energy Consumption. Such schemes are classified into active or passive mechanisms. Active techniques conserve energy by performing energy conscious operations, such as transmission scheduling and energy-aware routing. Mavromoustakis et al. in [112] considers the association of Energy conservation problem with different parameterized aspects of the traffic (like traffic prioritization) and enables a mechanism that tunes the interfaces scheduler to sprawl in the sleep state, according to the activity of the traffic of a certain node in the end to-end path in real-time. Preliminary research work of the above-mentioned issue, has been submitted for possible publication in [128], [129], [130].

Moreover, additional fields for future research may consider challenges related with transport layer issues, as the existing transport layer protocols, such as TCP, are not suitable for an environment where frequent disruption is a norm and end-to-end paths are typically not available such in some secondary usage scenarios. The critical fact is that, in such situations, the Transmission Control Protocol (TCP) often does not operate [131], [132], [133]. Moreover, the impact of Service Interruption Losses, sensing and negotiations delays in Cognitive Radio networks and their influence on legacy transport layer protocols has to be investigated. Towards this, in the transport layer, modifications have to be made to TCP and UDP working in a cognitive radio environment to avoid performance degradation. Congestion control in TCP depends on the packet loss rate and the round-trip-time (RTT). With a wireless link, a TCP sender could mis-interpret packet loss due to wireless error as a sign of congestion. As a result, congestion avoidance and slow start mechanisms would be invoked. Some variants of TCP were proposed to cope with this problem in a wireless environment. For example, an indirect-TCP (I-TCP) splits a connection of wireless link from the wired link, so that each TCP connection can be optimized for wireless and wired networks, respectively. In cognitive radio networks, many factors such as the transmit power, the bandwidth of the spectrum hole, and the interference level can affect the packet loss rate.

Similarly, RTT can be affected by the delay due to spectrum sensing and spectrum handoff, for which when the current channel becomes unusable for an unlicensed user, the unlicensed user has to search for a new channel. Therefore, the transport layer protocol has to consider these effects to optimize end-to-end rate control.

Last but not least, it is envisage that a very promising system architecture may utilize the proposed broker entity not only for coordinating the economics for spectrum trading/leasing, but also as part of the communication and data routing processes during inter-system networking. Towards this further research is required not only on architectural level, but also and more predominant at system design and configuration of the entire broker, so that to incorporate the appropriate communication and signalling interfaces for secondary systems' support, which may utilize heterogeneous radio technologies.

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ABBREVIATIONS

A	
AODV	Ad-hoc on Demand Distance Vector
ASO	Analogue Switch-Off
B	
BTD	Backward Traffic Difference
BW	Bandwidth
C	
CCC	Common Control Channel
CDMA	Code Division Multiple Access
COGEU	Cognitive Radio Systems for Efficient Sharing of TV White Spaces in European Context
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CR	Cognitive Radio
CRNs	Cognitive Radio Networks
D	
DL	Downlink
DSO	Digital Switch-Over
DSR	Dynamic Source Routing
DVB-H	Digital Video Broadcasting - Handheld
DVB-T	Digital Video Broadcasting - Terrestrial
E	
ETSI	European Telecommunications Standards Institute
F	
FCC	Federal Communications Commission
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
G	

GA	Genetic Algorithm
GBR	Guaranteed Bit Rate
GPRS	General Packet Radio Service
H	
HDTV	High Definition Television
I	
IEEE	Institute of Electrical and Electronic Engineering
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISM	Industrial Scientific and Medical Radio Bands
iTV	Interactive Television
L	
LCA	Least Cost Alternative
LTE	Long Term Evolution
M	
MAC	Media Access Control
MAP	Maximum Allowable Power
N	
Non-GBR	Non-Guaranteed Bit Rate
NPS	Number of Possible Solutions
NPV	Net Present Value
P	
PMSE	Programme Making and Special Events
PS	Primary Systems
Q	
QoS	Quality of Service
R	
RF	Radio Frequency
RREP	Rout Replay
RREQ	Route Request
RRM	Radio Resource Management

RTSSM	5.3.1. Real-time Secondary Spectrum Market
RTT	Round Trip Time
	S
SA	Simulated Annealing
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
SS	Secondary Systems
	T
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TTL	Time To Live
TVWS	Television White Spaces
	U
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
	V
VCG	Vickerey-Clark-Grooves
VHF	Very High Frequency
	W
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

APPENDIX A

Appendix A presents in detail the operation of the heuristics non-linear algorithms, as well as the selected parameters that have been used for the experimentation and the performance evaluation.

A.1 Simulated Annealing

Simulated annealing (SA) is a generic probabilistic meta-algorithm for the global optimization problem[1]. The name and inspiration come from annealing in metallurgy, a technique involving the heating and controlled cooling of a material to increase the size of its crystals and reduce their defects. The heat causes the atoms to become unstuck from their initial positions (a local minimum of the internal energy) and wander randomly through states of higher energy; the slow cooling gives them more chances of finding configurations with lower internal energy than the initial one. By analogy with this physical process, each step of the SA algorithm[2,3] replaces the current solution by a random “nearby” solution. This solution is chosen with a probability that depends on the difference between the corresponding function values and on a global parameter *T* (called the temperature). The temperature is gradually decreased during the process. The dependency is such that the current solution changes almost randomly when *T* is large, but increases “downhill” as *T* goes to zero. The allowance for “uphill” moves reduces the chance that the method gets stuck at a local minimum.

At each step (see Table 14), the SA heuristic considers a certain neighbor of the current state, and probabilistically decides between moving the system to a neighboring state or staying in the current state. The probabilities are chosen so that the system ultimately tends to move to states of lower energy. The probability is large when the temperature is high so that the algorithm will not be stuck in a certain local optimum. On the other hand, the probability is low since the probability of local optima is low. When the temperature is zero, the algorithm reduces to the greedy algorithm. Typically this step is repeated until the system reaches a state that is good enough for the application, or until a given computation budget has been exhausted.

```
Create initial solution S
Initialize temperature t
repeat
for i = 1 to iteration-length do
```

[1] Kirkpatrick, Scott. "Optimization by simulated annealing: Quantitative studies." Journal of statistical physics 34.5-6 (1984): 975-986.

[2] Hansen, Per Brinch, "Simulated Annealing" (1992). Electrical Engineering and Computer Science Technical Reports. Paper 170. http://surface.syr.edu/eecs_techreports/170

[3] E. Hossain, D. Niyato, Z. Han, “Dynamic spectrum access and management in cognitive radio networks”, first ed. Cambridge University Press, 2009.

5: Generate a random transition from S to S_i
6: If ($C(S) \geq C(S_i)$) then $S = S_i$
7: else if ($e^{(C(S)-C(Si))/(k \cdot t)} > random[0, 1)$) then $S = S_i$
8: Reduce temperature t
9: until (no change in C(S))
10: Return S

Table 14 Simulated Annealing process

As with a local search, the problem representation includes both a representation of the solution space and an easily computable cost function C(s) measuring the quality of a given solution. The new component is the cooling schedule, whose parameters govern how likely we are to accept a bad transition as a function of time.
At the beginning of the search, it is exploited randomness to explore the search space widely, so the probability of accepting a negative transition should be high. As the search progresses, the algorithm seeks to limit transitions to local improvements and optimizations. Table 15 presents[4] the selected parameters for the cooling schedule that exploited for the implementation of the Simulated Annealing.

Initial system temperature (100 - 1000)	100
Temperature decrement function	$tk = \alpha \cdot tk-1$
α factor ($0.8 \leq \alpha \leq 0.99$)	0.95
Number of iterations between temperature change (1-10)	3
Acceptance criteria	$C(s_i+1) < C(s_i)$ or $e^{-\frac{(C(s_i)-C(s_{i+1}))}{k \cdot t_i}} \geq r$
r factor: random number	$0 \leq r < 1$
Stop criteria	number of interations

Table 15 Simulated Annealing parameters

A.2 Genetic Algorithm

Genetic algorithms were invented to solve optimization problems using Darwin's natural evolution principle. Genetic algorithms are typically implemented by computer simulations. In a genetic algorithm, a population is a collection of individuals (i.e. chromosomes). This individual represents the candidate solution to an optimization problem. The population evolves so that the better solution can be reached. The evolution of the population in a genetic algorithm uses probabilistic rules rather than deterministic rules. Also, a genetic algorithm relies on many chromosomes, which represent different points in the problem. As a result, a genetic algorithm can avoid obtaining locally optimal solutions, which are common in a non-convex problem. In addition, since a genetic algorithm requires only the evaluation of the objective function, it can perform without knowing the exact expression of the objective function. With these advantages, genetic algorithms are used to solve many optimization

[4] Steven S. Skiena, "The Algorithm Design Manual", Second Edition, Springer, ISBN: 978-1-84800-069-8

problems[5], especially those with non-convex objective functions. In a genetic algorithm, the decision variables to be optimized are encoded into a chromosome. While there are different choices of encoding schemes, the most common scheme is a binary string. In this case, the decision variable of an optimization is transformed into a sequence of 0s and 1s.

This population of chromosomes evolves and a new generation is created. The major operations in the evolution are as follows[6,7]:

- Reproduction: In this operation, the chromosomes in the current population are selected with a certain probability based on their goodness. These selected chromosomes are re-copied to produce a new population. The new population is defined as the successive generation.
- Crossover: In this operation, two chromosomes are randomly selected according to their goodness and then their sub-strings (whose locations in the original strings are randomly chosen) are interchanged.
- Mutation: In this operation, a chromosome is randomly selected according to its goodness. Then, some bits which are randomly chosen in the selected chromosome are altered (e.g. complemented from 0 to 1 and from 1 to 0). The resulting chromosome, after its bits are altered, is included in the new generation.

Each chromosome is characterized by its goodness (i.e. fitness), which is referred to as the fitness function. The fitness of a chromosome is a direct function of the objective in the optimization problem (but not necessarily the same). In a genetic algorithm, the population is evolved so that its chromosomes contain the highest fitness function in the case of maximization. In particular, the chromosome with the highest fitness will be reproduced most often. As a result, the globally optimal solution will be reached. Note that this fitness function is defined to be different from the objective function of the problem so that it can be suitably used by the reproduction operation.

1: Choose the population of random initializations
2: repeat
3: Evaluate the fitness of each chromosome
4: Select pairs of best-ranking chromosomes to reproduce
5: Apply crossover operation
6: Apply mutation operation
7: until Stop criteria are met

Table 16 Genetic Algorithm process

The process of a genetic algorithm is shown in Table 16. The algorithm will be terminated if the stop criteria are met. The stop criterion can be defined as the maximum number of iterations. Alternatively, the mean and the maximum fitness values of the population can be observed. If these two values reach a predefined threshold, the algorithm will stop. In this case, it is likely that the chromosomes in the population will encode the points which are close

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5 Bhattacharjee, Subhasree, Amit Konar, and Atulya K. Nagar. "Channel Allocation for a Single Cell Cognitive Radio Network Using Genetic Algorithm." Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2011 Fifth International Conference on. IEEE, 2011.

6 E. Hossain, D. Niyato, Z. Han, "Dynamic spectrum access and management in cognitive radio networks", first ed. Cambridge University Press, 2009.

7 Nair, T. R., and Kavitha Sooda. "Comparison of Genetic Algorithm and Simulated Annealing Technique for Optimal Path Selection In Network Routing." arXiv preprint arXiv:1001.3920 (2010).

to the optimal solution. Moreover, Table 17 presents the selected parameters[8,9,10] that exploited for the implementation of the Genetic Algorithm. It has to be noted that the crossover method is assumed to be one or two point crossover. The mutation rate given above is 'per bit', whereas in many public domain codes, the mutation rate is input as a 'per chromosome' probability.

Population size	50
Number of generations	100
Crossover type	typically two point
Crossover rate	0.6
Mutation rate	0.001
Stop criteria	number of interations

Table 17 Genetic Algorithm parameters

[8] DeJong, K.A. and Spears, W.M. "An Analysis of the Interacting Roles of Population Size and Crossover in Genetic Algorithms," Proc. First Workshop Parallel Problem Solving from Nature, Springer-Verlag, Berlin, 1990. pp. 38-47.

[9] Grefenstette, J.J. "Optimization of Control Parameters for Genetic Algorithms," IEEE Trans. Systems, Man, and Cybernetics, Vol. SMC-16, No. 1, Jan./Feb. 1986, pp. 122-128.

[10] Goldberg, and Deb, (1991). A comparative analysis of selection schemes used in GAs. In G. Rawlins (Ed.), Foundations of GAs (FOGA). San Mateo, CA: Morgan Kaufmann, 69--93.

APPENDIX B

Appendix B presents some preliminary experimental results obtained in a controlled conditions environment (simulation test-bed) concerning the performance of the proposed RMM when the optimisation process is realised by the Backtracking (with Pruning), the Simulated Annealing and the Genetic algorithms respectively.

The experimental test-bed comprised:

- A TVWS Occupancy Repository, where only 10 TV channels (between Ch.40 and Ch.60) are available for exploitation by Secondary Systems, resulting in a total/aggregate bandwidth of 80MHz with an initial spectrum utilisation of 19.05% and initial fragmentation of about 0.76817.
- A Spectrum Trading and Policy Repository, hosting information about the TVWS selling/leasing procedure, as well as the spectrum-unit price to be exploited during the trading process. It should be noted that in our tests, the fixed-price policy was selected, based on a single spectrum-unit price that was applied for every TVWS frequency trading process.
- A number of Secondary Systems with different radio characteristics/requirements that were simultaneously competing for the available TVWS. These systems were based on LTE operating with Time-Division-Duplexing (TDD), WiFi and Public Safety technologies. Moreover, for every system a different QoS-level requirement was selected, thus the optimisation algorithm was also taking into account this parameter during the spectrum allocation process. Additionally, for every new simulation-test (namely as Time Period in our experiments) the secondary systems were entering the test-bed, under a fixed schedule, requesting access to the available (at the given Time Period) TVWS frequencies.

Based on this test-bed, five experiments were designed and conducted as follows:

- First simulation scenario/Time Period 1: "LTE 1[11]" system is requesting access to TVWS up to time period 2.
- Second simulation scenario/Time Period 2: "LTE 1" maintains access to the spectrum, while two new secondary systems "Public Safety 1[12]" and "WiFi 1[13]" are requesting access to the spectrum up to time periods 5 and 4, respectively.
- Third simulation scenario/Time Period 3: "LTE 1" releases the occupied spectrum as well as the "Public Safety 1" and "WiFi 1" maintain their access to TVWS. Also, two new secondary systems ("LTE 2[14]" and "Public Safety 2[15]") are accessing the available spectrum up to time period 5.

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[11] Power: 4 Watt, Bandwidth: 20MHz, QoS: Medium

[12] Power: 0.1 Watt, Bandwidth:1 MHz, QoS: High

[13] Power: 0.25 Watt, Bandwidth: 22 MHz, QoS: Low

[14] Power: 4 Watt, Bandwidth: 10 MHz, QoS: Medium

- Fourth simulation scenario/Time Period 4: "Public Safety 1", "WiFi 1", "LTE 2" and "Public Safety 2" are still operating, while two new secondary systems, "LTE 3[16]" and "WiFi 2[17]", are accessing the available spectrum, up to time period 5.
- Fifth simulation scenario/Time Period 5: "WiFi 1", "WiFi 2" and "LTE 3" release the occupied TVWS, while "Public Safety 1", "Public Safety 2" and "LTE 2" are still operating. During this simulation scenario "LTE 4[18]" and "WiFi 3[19]" systems are requesting access to the spectrum.

Fig. B-1 – Fig. B-4 depict the results obtained in every Time Period for each RRM implementation, as a matter of spectrum utilization, spectrum fragmentation and simulation time.

- Spectrum utilisation was estimated as the percentage of the exploited bandwidth (by both Primary and Secondary Systems) over the totally available spectrum within TV channel 40-60, (i.e. 168MHz). In Fig. B-1 – Fig. B-4 (a) Time Period "0" represents the spectrum utilization when only primary systems operate in the TVWS channels. From these figures it can be verified that all-four algorithms result in the same spectrum utilisation (for each Time Period), given that the same number of secondary systems was accommodated.
- Moreover, Fig. B-1 – Fig. B-4 (b) represents a qualitative comparison among Backtracking (with and without Pruning technique), Simulated Annealing and Genetic algorithms, as a matter of the duration of the simulation before obtaining the optimum solution. From these figures it can be observed that that Simulated Annealing and Genetic Algorithm perform better than Backtracking one regarding the simulation time, while the Pruning technique alleviates their differences.
- Finally, spectrum fragmentation was calculated by taking into account the number of fragments (unused spectrum-portions) as well as the size/bandwidth of each individual fragment. Fig. B-1 – Fig. B-4 (c) depicts the results obtained in every Time Period for each RRM implementation, where the Time Period "0" denotes the initial condition when no secondary system is accommodated. From these figures it can be verified that all algorithms provide an acceptable fragmentation score, taking into account that: a) the value "0" represents an "un-fragmented" spectrum, while when moving towards "1" the spectrum becomes more-and-more fragmented, i.e. there exist many blocks of unexploited frequencies.

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[15] Power: 0.1 Watt, Bandwidth:1 MHz, QoS: High

[16] Power: 4 Watt, Bandwidth: 20 MHz, QoS: Medium

[17] Power: 0.25 Watt, Bandwidth: 22 MHz, QoS: Low

[18] Power: 4 Watt, Bandwidth: 5MHz, QoS: Medium

[19] Power: 0.25 Watt, Bandwidth: 22 MHz, QoS: Low

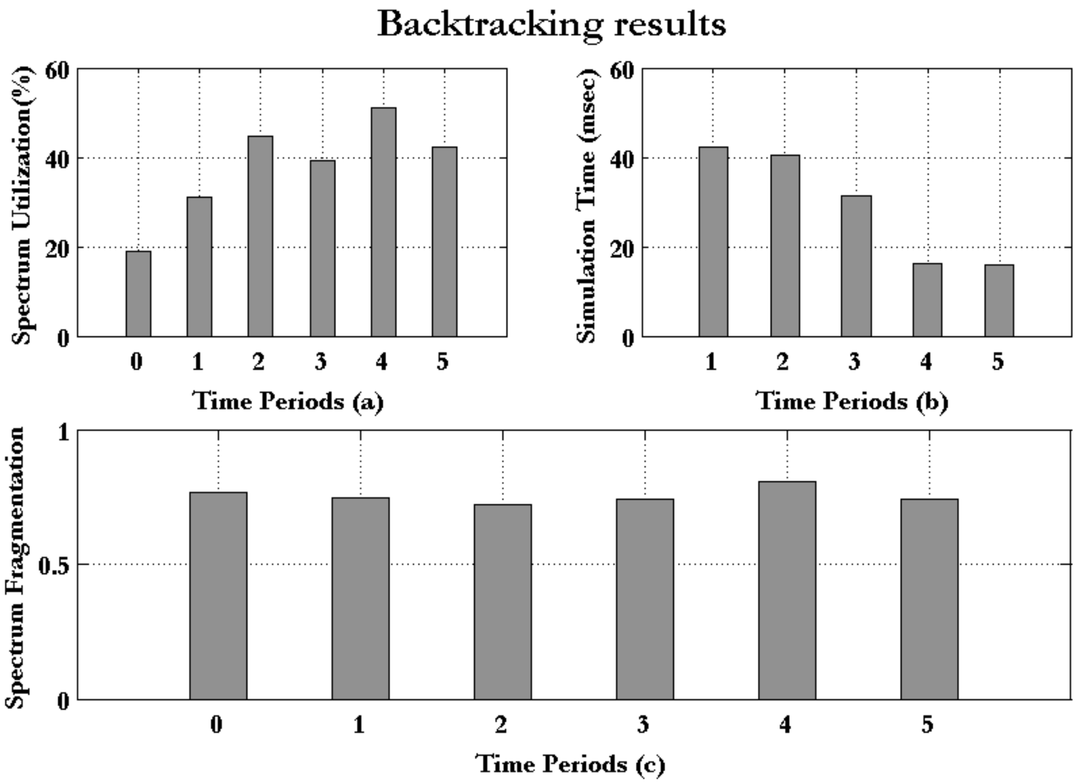

Fig. B-1 Backtracking Algorithm performance evaluation

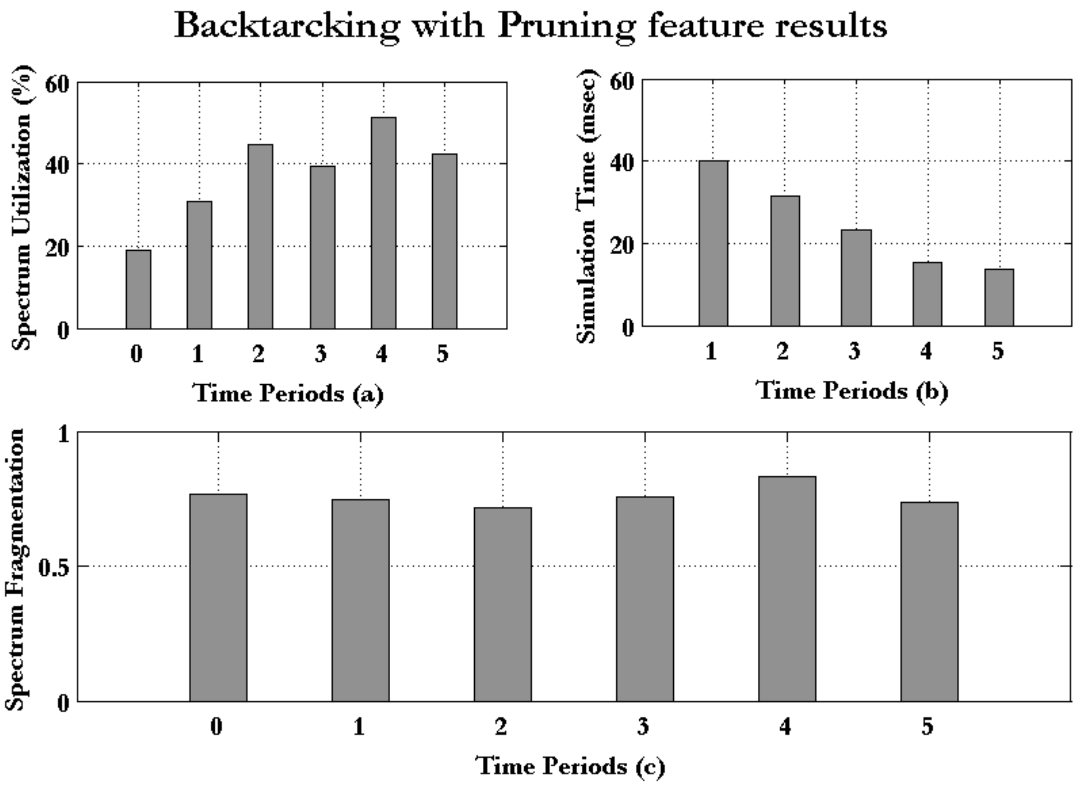

Fig. B-2 Backtracking with Pruning feature performance evaluation

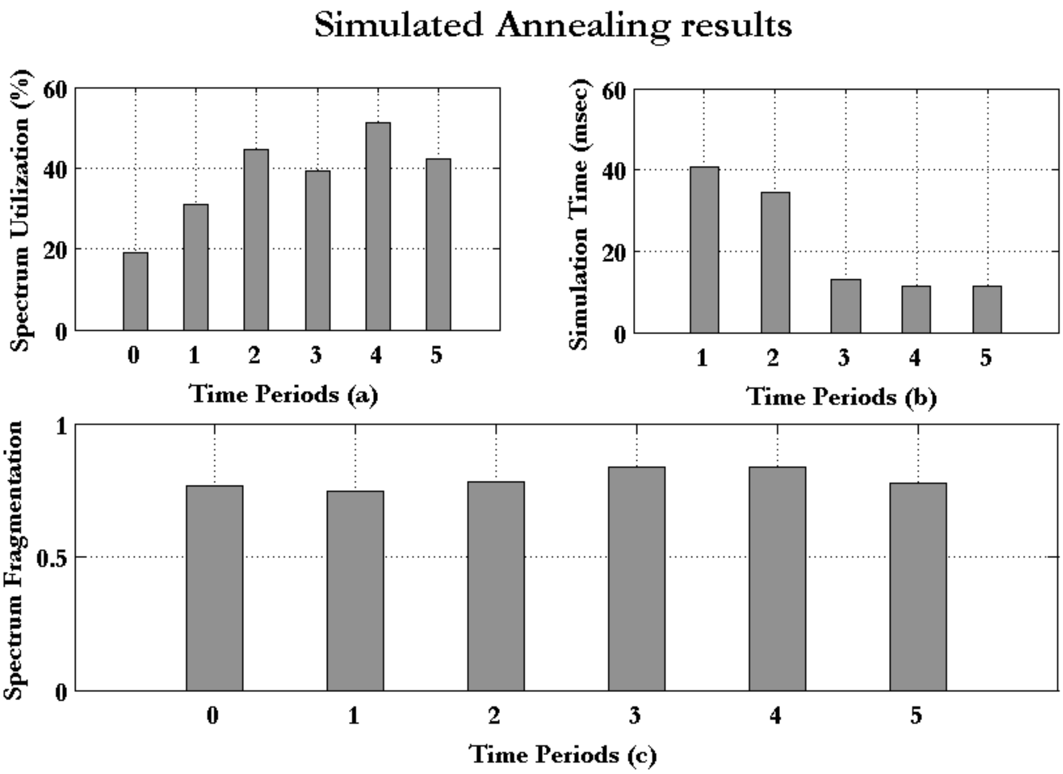

Fig. B-3 Simulated Annealing Algorithm performance evaluation

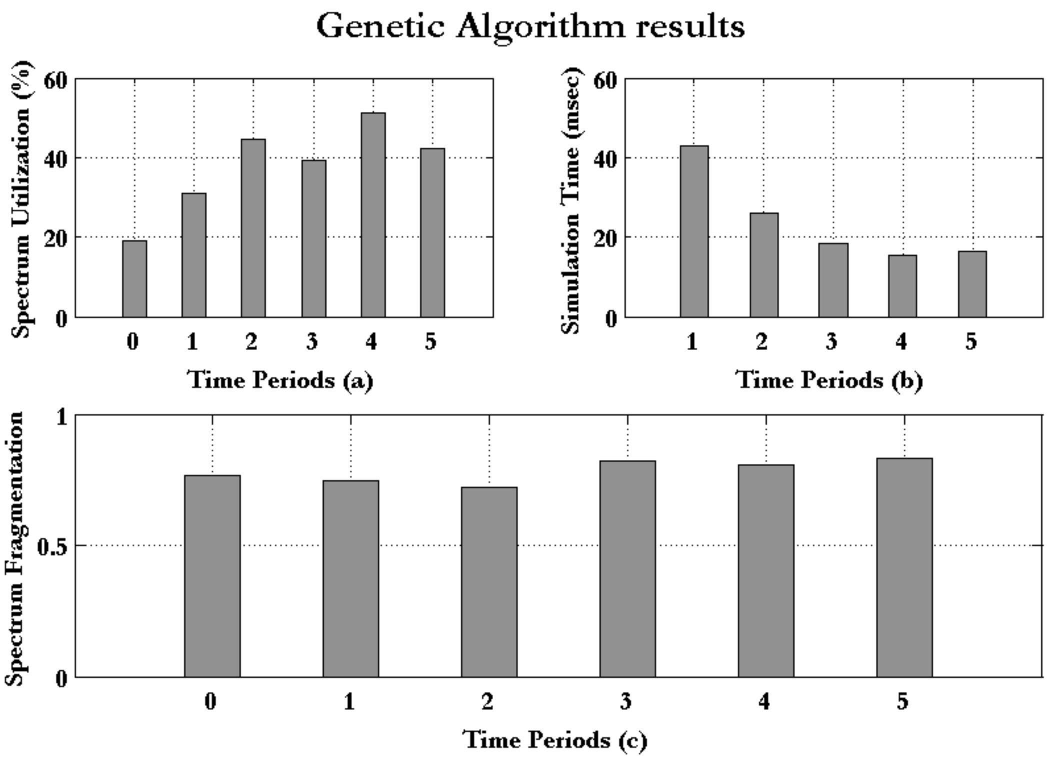

Fig. B-4 Genetic Algorithm performance evaluation

Fig. B-5 and Fig. B-6 represent the TVWS allocation results during the first and the second time period, utilising Simulated Annealing. It can be observed in Fig. B-5 that channels 58, 59 and 60 are allocated to “LTE1” system, which requests access to TVWS during the first time period. Furthermore, it can be seen in Fig. B-6 that the “Public Safety 1” and the “WiFi 1” systems are granted channel 40 and channels 50 up to 52 respectively. Additionally, a very interesting outcome is related to the broker’s capability in accommodating secondary systems when the available TVWS spectrum is shorter than the total requested bandwidth, and therefore only part of the competing systems can be served. In such a case, the broker takes into account the priority level of each secondary system, and grants access only to those of the highest level. For example, during Time Period 3 (see Fig. B-7), there are already four secondary systems active (i.e. “Public Safety 1”, “WiFi 1”, “LTE 2” and “Public Safety 2”), and the total available spectrum sums about 32MHz, scattered within TV channel 46, 58, 59 and 60. For this spectrum two more secondary systems are competing, i.e. “LTE 3” of medium priority level requesting 20MHz, and “WiFi 2” of low priority level requesting for 22MHz. Evidently, while both “LTE 3” and “WiFi 2” are competing for the spectrum within channel 58 to channel 60, only one of them is served (see Fig. B-8), i.e. that of the higher priority (“LTE 3”). Finally, Fig. B-9 depicts the TVWS allocation results when “WiFi 3” and “LTE 4” systems are granted access to the available spectrum during the time period 5.

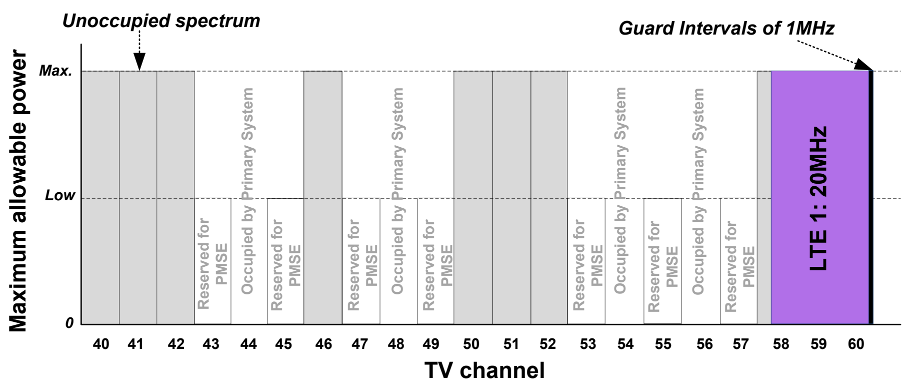

Fig. B-5 TVWS allocation during the Time Period 1

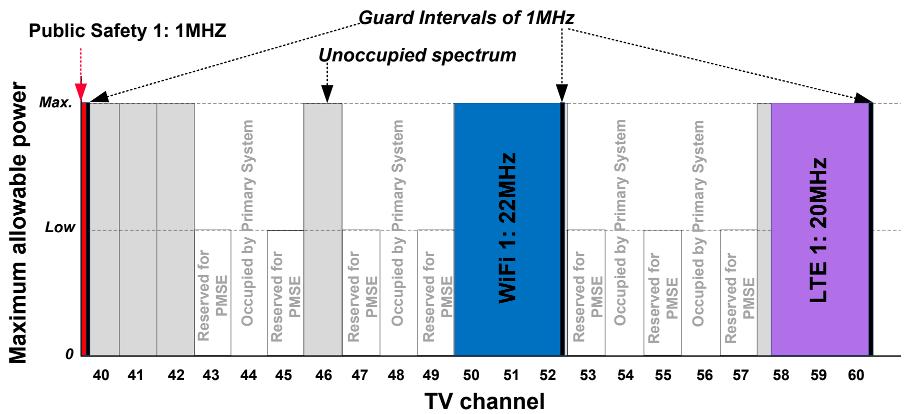

Fig. B-6 TVWS allocation during the Time Period 2

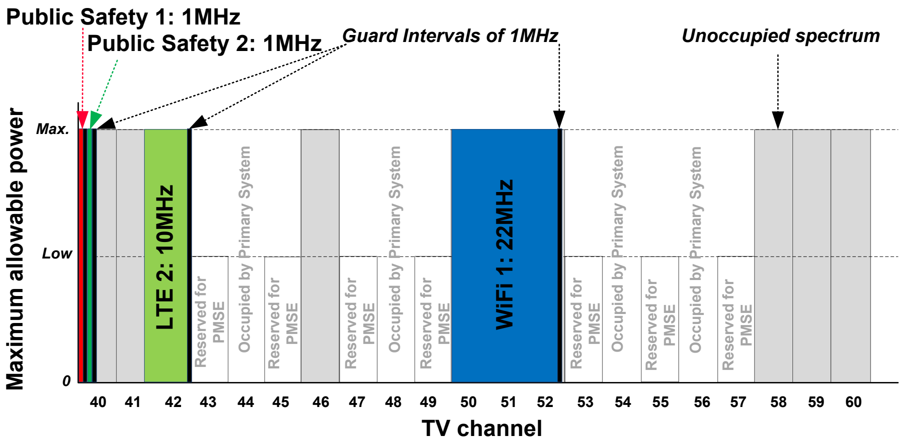

Fig. B-7 TVWS allocation during the Time Period 3

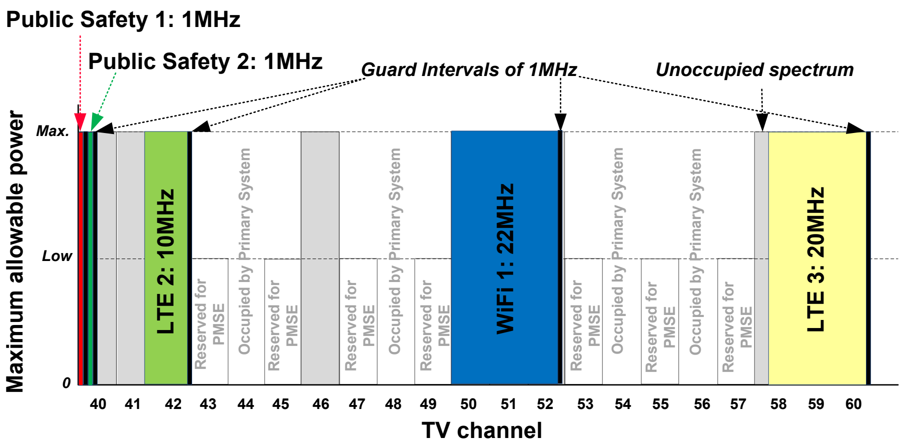

Fig. B-8 TVWS allocation during the Time Period 4

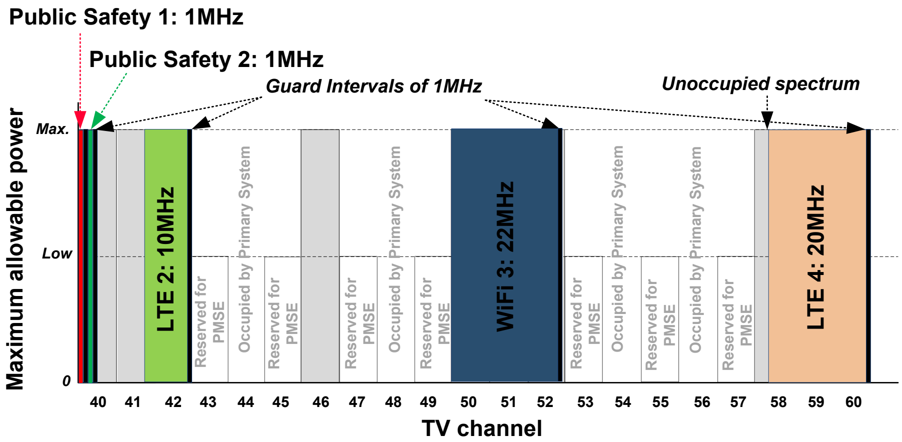

Fig. B-9 TVWS allocation during the Time Period 5