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PROPOSAL AND EVALUATION OF CHANNEL ASSIGNMENT ALGORITHMS FOR WIRELESS LOCAL AREA NETWORKS WITH OPPORTUNISTIC SPECTRUM ACCESS CAPABILITIES

PhD Thesis Dissertation

by

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To God my Lord for giving me the fortitude to achieve this goal.

Summary

The growing need for wireless connectivity is pushing the massive adoption and usage of Wireless Local Area Networks (WLANs) based on the IEEE 802.11 standard (Wi-Fi), leading to dense deployments of individual, uncoordinated access points (AP) in highly populated areas. By 2016, over half of the world's Internet traffic is expected to come from WLAN connections, according to the latest Cisco® Visual Networking Index (VNI) Forecast (2011-2016). The proliferation of dense deployments causes high interference levels in the unlicensed bands (i.e. ISM bands) available for WLAN operation, which, ultimately, may result in both an unpredictable degradation in network performance and unfairness among APs.

Channel assignment mechanisms are the central tool used nowadays for mitigating the interference problems in the ISM band caused by neighboring APs. However, regardless of the ability of different channel assignment algorithms to improve WLAN performance, the amount of available spectrum in unlicensed bands for WLAN use may still constitute a key limiting factor in high dense deployments. In this context, the exploitation of additional portions of the radio spectrum bands that are assigned to a particular application or service but remain unused or unoccupied at specific locations and times can help to further improve the performance of WLANs networks. This spectrum usage concept is known in the literature as Opportunistic Spectrum Access (OSA), where *secondary users* are allowed to share the same frequencies used by some *primary users* whenever these primary services are not disturbed.

This thesis work has addressed a novel study for OSA-enabled WLANs in which the possibilities and benefits offered by WLANs using OSA capabilities are discussed and quantified. This thesis provides two main contributions.

The first contribution is the development of the formulation and assessment of the spatial availability of a certain spectrum segment within indoor locations in dense urban areas in order for it to be opportunistically reused by WLANs. To this end, the interference conditions between primary and secondary users have been established along with the necessary propagation models accounting for outdoor, indoor and outdoor-to-indoor losses. Considering the service area of a primary system devoted to providing outdoor coverage, the proposed model has been used to compute the percentage of indoor locations where the secondary users can actually reuse the primary frequency band without interfering with the primary system.

The second contribution is the proposal, development and evaluation of a set of channel assignment algorithms that allow WLANs to operate on available channels in both unlicensed ISM and OSA-enabled spectrum bands. Unlike the classical schemes for legacy WLANs, the proposed algorithms cope with two distinguishing issues arising in the OSA-enabled WLAN channel assignment problem: channel prioritization and spectrum heterogeneity. To that end, a system model is developed to describe and represent the main components involved in an OSA-enabled WLAN scenario. The model allows setting up a network scenario with primary and secondary systems, determining the list of available primary channels for each WLAN and defining the channel assignment constraints for WLANs. From this basis, the thesis has first formulated the channel assignment problem for OSA-enabled WLANs as a Binary Linear Programming (BLP) problem, which has been optimally solved by means of branch-and bound (BB) algorithms and used as a benchmark. Motivated by the need to have more computationally efficient solutions than that offered by the BB algorithm, a number of centralized and distributed heuristic algorithms have been proposed, encompassing simulated annealing (SA) techniques and the construction of minimum spanning tree (MST) graphs to reduce the level of coupling between neighboring APs. The algorithms have been evaluated under different conditions of AP density and spectrum availability and compared to the optimal solution as well as classical algorithms proposed for legacy WLANs.

Acknowledgements

This thesis is dedicated to:

My beloved wife Angie who, with her love, patience and dedication, has always been at my side supporting me.

My beloved sons, David Francisco and Carlos Francisco, who are my reason to improve every day.

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List of Abbreviations

AP	Access Point
BB	Branch and Bound
BLP	Binary Linear Programming
BS	Base Station
BSS	Basic Service Set
COGNEA	Cognitive Networking Alliance
CPE	Customer Premise Equipment
CR	Cognitive Radio
DS	Distribution System
DSA	Dynamic Spectrum Allocation
DSSS	Direct Sequence Spread Spectrum
ECC	Electronic Communications Committee(of Europe)
ECMA	European Computer Manufacturers Association
ESS	Extended Service Set
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission(of US)
FF	First Fit
HPBW Az	Half Power Beam Width, Azimuth Angle
IBSS	Independent Basic Service Set
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming
IPTV	Internet Protocol Television
ISM	Industrial, Scientific and Medical band
LCCS	Least Congested Channel Search
LOS	Line Of Sight
MST	Minimum Spanning Tree
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PB	Primary Band

PSD	Power Spectral Density
PU	Primary User
QoS	Quality of Service
RF	Radio Frequency
SA	Simulated Annealing
SDO	Saturation Degree Order
SH	Spectrum Holes
STA	Associated WLAN Client Stations
SU	Secondary Users
TV	Television
TVWS	TV White Space
UHF	Ultra High Frequency
US	United States
UWB	Ultra Wide Band
VHF	Very High Frequency
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network
WS	White Space

Chapter 1. **Introduction**

1.1 Scope and Motivation

Nowadays, the use of Wireless Local Area Networks (WLANs) technology is on the rise, on both public (e.g., airports, train stations, leisure parks, etc.) and private premises (offices, hotels, home) along with the dependence of people on wireless connections for access to the Internet.

As a matter of fact, wireless local area networks are now the predominant access technology for mobile devices such as laptops, tablets, and eReaders, since approximately 50 percent of these devices connect to the Internet exclusively through this technology. Also, on average, smartphone users use WLAN one-third of the time to connect their devices to the Internet despite having cellular coverage, as reported in [1]. As a consequence of this predominance, the WLAN market posted record revenues in the third quarter and a 19 percent revenue growth over the same period in 2011. This led to eight WLAN vendors achieving their highest ever quarterly results in the same year, as reported in [2].

Each WLAN device makes a shared and non-preferential use of unlicensed bands, with the industrial, scientific and medical (ISM) band at 2.4 GHz being the most used [3]. Thereby, highly dense WLAN deployments could lead to excessive levels of interference in the commonly used band that could deteriorate network performance. Highly dense WLAN scenarios can arise from large-scale enterprise WLAN network deployments as well as a result of multiple individual WLAN installations in residential buildings (e.g., SOHO, Small Office Home Office use cases). Moreover, the potential adoption of WLAN-based mesh networks can also lead to a high concentration of Access Points (APs) in a limited geographical area.

In this context, channel assignment mechanisms constitute the main tool in reducing the level of interference between neighboring WLANs as much as possible in order not to impair individual network performance.

Thus far, the WLAN channel assignment problem in unlicensed bands (e.g. 2.4 and 5GHz ISM bands) has received a lot of attention in the research community [4], [5], [6], [7]. However, regardless of the ability of the different channel assignment algorithms to improve WLAN performance, the amount of available spectrum in unlicensed bands for WLAN use can still constitute a key limiting factor in dense deployments, especially where there is a need to operate in bands with good propagation conditions (e.g. only 3 non-overlapping channels are available in the 2.4 GHz ISM band).

Hence, the exploitation of additional bands for WLANs (e.g., licensed bands that can be used opportunistically) can help improve the performance of such networks. WLAN devices (i.e. Access Points, APs, and associated stations, STAs) would serve as license-exempt secondary users (SU) of these additional bands and would use them without causing interference to primary users (PUs) holding spectrum usage rights to the bands. This spectrum usage concept is known in the literature as Opportunistic Spectrum Access (OSA) [8], [9], [10]. OSA is a dynamic spectrum access model aimed at improving spectrum utilization by allowing more services/users to share the same band according to a hierarchical access structure with primary and secondary users.

Also, it is well-known that the electromagnetic spectrum is limited and the mechanism commonly used by government regulatory agencies for assigning certain segments of this consists in providing a license to the telecommunications operator for exclusive use of certain segments of spectrum (i.e. frequency bands) in a limited area. However, this licensed spectrum is not always exploited 100%. Because of this, the potential availability of unused portions of the radio spectrum (i.e. white spaces, WS) to be exploited opportunistically is supported by some recent studies which confirm the very low spectrum occupancy of certain licensed bands [11], [12]. Moreover, even when a licensed band is permanently used by a primary user to provide outdoor service coverage, some studies on spatial availability of spectrum [13] show that this licensed band could also be opportunistically reused within indoor building locations where many WLAN are expected to operate.

One of the first bands that has been studied and regulated for opportunistic use is the TV band [14]. So, for instance, an initial analysis of TV White Space availability developed in the United Kingdom (UK) has determined that, for a device emitting in TV white spaces with a power of 10dBm, 50% of the populated pixels (i.e. pixel: 100m by 100m squares) have access to approximately 144MHz of spectrum [14]. This fact has led to the consideration of unlicensed access to TV bands by WLAN devices in some research works and market initiatives [15], [16]. As an example, White-fi is a term being used to describe the use of Wi-Fi technology within the unused TV spectrum, or TV white space. The IEEE 802.11af [15] working group has been set up to define a standard to implement this. Under this OSA-enabled WLAN view, appropriate channel assignment mechanisms are needed to choose the operational channel in each AP among those available either in unlicensed bands or in an opportunistically exploited licensed band.

Therefore, in this thesis, a novel study framework for OSA-enabled systems is proposed (see, Figure 1.1), where the benefits that could be achieved by using OSA capabilities are quantified. Thus, the main motivation behind this thesis is to alleviate spectrum congestion problems in overcrowded unlicensed bands, especially in highly dense WLAN deployments, by allowing WLANs to exploit OSA. In order to achieve such a proposal, several mechanisms of channel assignment with OSA capabilities are developed.

For this, it is considered that the WLANs can access the use of a channel from among those existing within the unlicensed band or, under some circumstances, a channel within unused portions in additional frequency bands that have been destined for providing some kind of wireless communication services to other users (i.e. primary users). The access to the OSA-enabled bands allows WLANs to operate in this additional spectrum segment as secondary users, while primary users and services are not interfered with or affected. This access mode does not guarantee secondary users any type of protection, given that the priority for using this band belongs to the primary users.

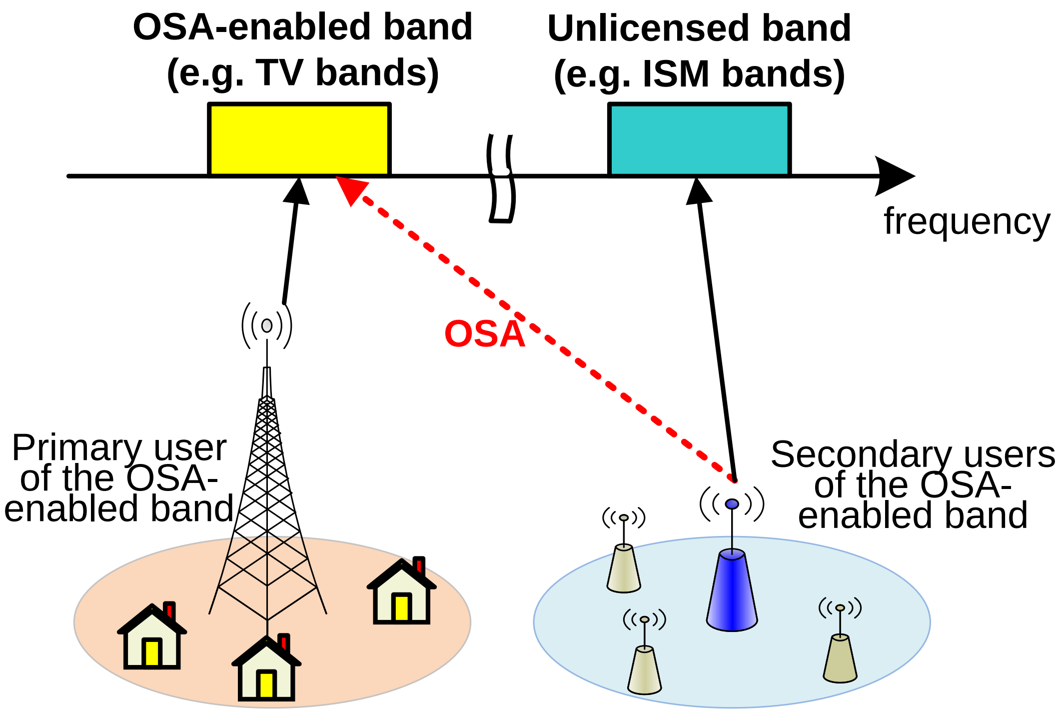


Figure 1.1: Proposed Study Framework

1.2 Objectives

Motived by the benefits that OSA capabilities are expected to bring into the operation of WLAN, this thesis pursues the following main research objectives:

- Determine and analyze the spatial availability of a certain spectrum segment within indoor locations in dense urban areas, in order for it to be opportunistically reused by WLANs.
- Characterize the scenario and the system model which allow for the study of channel assignment algorithms for WLANs in OSA-enabled scenarios.
- Develop and evaluate several channel assignment algorithms that allow WLANs to operate in available channels in both unlicensed ISM and OSA-enabled licensed bands, in order to improve the performance of such networks.

1.3 Thesis Organization

Thesis structure illustrated in Figure 1.2 describes how each chapter and their obtained products interact with each other. Chapter 2 establishes basic definitions and concepts needed for the opportunistic spectrum usage. Furthermore, the required components for implementing a system with OSA are described. Also, several applications developed with OSA capabilities are presented in this chapter. Next, in this chapter, a brief overview of WLANs is provided, followed by a description of the main architectures and components. Then, some cases of spectrum management in WLANs are presented, and, among them, descriptions of operating bands utilized by WLANs and several techniques for channel assignment.

Chapter 3 is based on concepts and definitions previously established in Chapter 2. This chapter analyses the possibility of exploiting OSA for short-range radio communications systems within indoor locations in dense urban areas. In particular, considering the service area of a primary system devoted to providing outdoor coverage in a dense urban scenario, the percentage of indoor locations where the secondary users can reuse the primary frequency band without disturbing the primary system or being disturbed is estimated. To this end, a set of conditions for the primary spectrum reuse by secondary users is defined. Results of this analysis allow for the spectrum reusable zones where the opportunistic access by WLANs could be implemented to be determined. Next, obtained results provide the amount of reusable area where the primary spectrum is available (i.e. spaces inside buildings where the primary spectrum is available are calculated), in order that opportunistic access by WLANs can be performed.

In Chapter 4, a system model intended to describe and represent the main components involved in an OSA-enabled WLAN scenario is developed. The system model is the basis for the development and performance evaluation of the channel assignment algorithms presented in the next chapter. This model allows for the configuration of a network scenario with primary and secondary systems. The deployment layout and the main power and spectrum usage parameters can be configured differently for each system. It also supports the planning of frequencies to be assigned to each primary device. The coverage and inference zones among users of both systems are described by a set of usage and interference areas defined for each device. These areas are computed by using propagation and interference models. An interference-based metric that allows the interference level between a pair of APs to be quantified when using a certain pair of channels either from ISM band or primary band is defined. Then, a set of interference conditions is defined in order to obtain a list of available primary channels for each WLAN. Also, channel assignment constraints for WLANs are defined. Additionally, the network scenario is represented as a graph in order to facilitate the analysis of these systems. Finally, in this chapter, a case study is proposed in order to analyze the deployment of users on the scenario, usage and interference areas, interference levels among users and available primary channels.

In Chapter 5, novel channel assignment mechanisms jointly considering available channels in both unlicensed ISM and OSA-enabled licensed bands are developed and evaluated. Unlike classical schemes proposed for legacy WLANs, channel assignment mechanisms for OSA-enabled WLAN address two distinguishing issues: channel prioritization and spectrum heterogeneity. The first one refers to the fact that additional prioritization criteria other than interference conditions should be considered when choosing between ISM and licensed band channels. The second refers to the fact that channel availability might not be the same for all WLAN Access Points because of primary user activity in the OSA-enabled bands.

In this chapter, the channel assignment problem for OSA-enabled WLANs is formulated in the context of scenarios with coordinated and uncoordinated WLAN deployments, where the computation of the solution can be carried out in a centralized or distributed manner. Thus, the channel assignment problem is formulated as a Binary Linear Programming Problem (BLP) establishing the objective and several constraints in order to obtain optimal solutions. The resulting BLP problem is optimally solved by means of branch-and bound algorithms and used as a benchmark to develop more computationally efficient heuristics. Upon such a basis, several novel channel assignment algorithms based on well-known resource assignment heuristics and which are able to exploit both channel prioritization and spectrum heterogeneity are proposed. The algorithms are evaluated under different conditions of AP density and primary band availability. These proposals have been developed and evaluated by taking note of the parameterized model for opportunistic scenarios and the metric proposed in Chapter 4.

Finally, this thesis concludes in Chapter 6 with final conclusions and main contributions of the work developed and future works.

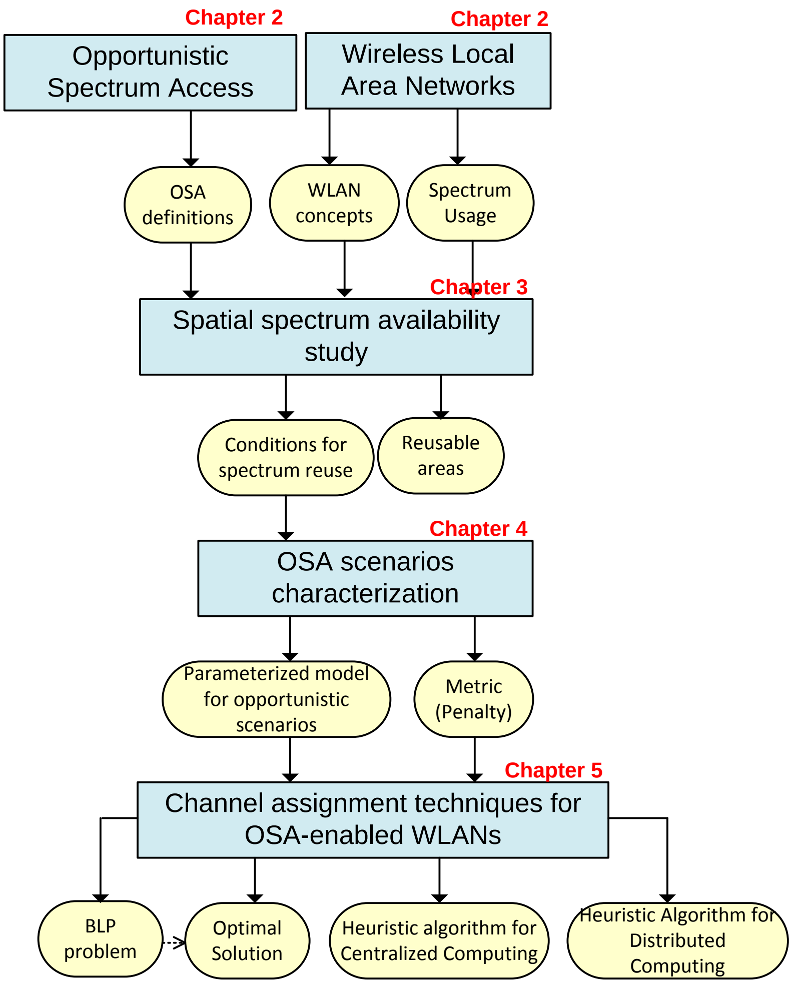


Figure 1.2: Thesis Structure

1.4 Main Outcomes

1.4.1 Publications

Part of the content of this thesis has been published in journals, international conferences, and technical reports during the period of research of the author in the Mobile Communication Research Group of the Department of Signal Theory and Communications, at Universitat Politècnica de Catalunya. A list of these works is given below:

- F. Novillo, R. Ferrús "Channel assignment algorithms for osa-enabled WLANs exploiting prioritization and spectrum heterogeneity", IEICE Transactions on Communications vol.e95-b no.4 pp.1125-1134,apr. 2012.
- Novillo, F.; Ferrus, R.; , "Distributed channel assignment algorithm based on simulated annealing for uncoordinated OSA-enabled WLANs," Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2011 Sixth International ICST Conference on , vol., no., pp.81-85, 1-3 June 2011
- Novillo, F.; Ferrus, R.; Agusti, R.; Nasreddine, J.; , "Opportunistic channel allocation algorithms for WLANs based on IEEE802.11," Future Network and Mobile Summit, 2010 , vol., no., pp.1-8, 16-18 June 2010.
- Novillo, F.; Churchman, M.; Ferrus, R.; Agusti, R.; , "A channel allocation algorithm for OSA-enabled IEEE 802.11 WLANs," Wireless Communication Systems, 2009. ISWCS 2009. 6th International Symposium on , vol., no., pp.468-472, 7-10 Sept. 2009.
- Novillo, F.; Galeana, H.; Ferrus, R.; Agusti, R.; , "Spectrum Availability in Indoor Locations for Opportunistic Spectrum Access in Dense Urban Scenarios," Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th , vol., no., pp.1-5, 26-29 April 2009.
- "Final report on the activities and results of WPR11", NEWCOM++ Project Deliverable DR11.3, Editor(S): S. Palazzo, A. Leonardi (CNIT-CT), Contributors: L. Galluccio, G. Morabito, S. Palazzo, C. RAmetta (CNIT-CT); M. Reineri, C.-F. Chiasserini (CNIT-TO); F. Fabbri, R. Verdone (CNIT-BO); A. Zanella, A. Bardella (CNIT-PD); M. Franceschinis, M. Spirito (ISMB), R. M. Rocha, J. Soares (IST-TUL), A. Brunstrom, A. Kassler, A. Laven, M. Castro, P. Dely (KAU), T. Pérennou (CNRS-LAAS); M. D. De Amorim, M. Boc (CNRS-LIP6); A. L. Moustakas (IASA); R. Ferrus, F. Novillo (UPC); J. Nasreddine, J. Riihijärvi (RWTH).
- "State of the art of research on opportunistic networks, and definition of a common framework for reference models and performance metrics", NEWCOM++ Project Deliverable DR11.1, Editor(S): Sergio Palazzo, CNIT-CT, Contributors: R. Scopigno, M. Spirito (ISMB); I. Korpeoglu, A. R. Ulucinar (BILKENT/KHAS); A. L.Moustakas (NKUA/IASA); L. Galluccio, A. Leonardi (CNIT-CT); F. Fabbri, R. Verdone (CNIT-BO); C.F. Chiasserini (CNIT-TO); A. Zanella, F. Zorzi (CNIT-

PD); R. Ferrus, F. Novillo (UPC); M. Boc, M. Dias De Amorim (CNRS/LIP6); J. Riihijarvi (RWTH); A. Brunstrom, M. Cavalcanti De Castro (CHAL/KAU); L.D. Pedrosa (IST-TUL); D. Traskov (TUM).

Other works published during the research period:

- Novillo, F.; Galeana, H.; Lainz, A.; Ferrus, R.; Olmos, J.; , "Performance analysis of transport and radio load balancing strategies for BS assignment in mobile access networks," Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on , vol., no., pp.1-6, 15-18 Sept. 2008.

- Galeana, H.; Novillo, F.; Ferrus, R.; , "A Cost-Based Approach for Base Station Assignment in Mobile Networks with Limited Backhaul Capacity," Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008. IEEE , vol., no., pp.1-6, Nov. 30 2008-Dec. 4 2008.

- Hiram Galeana, Francisco Novillo, Ramon Ferrús, Joan Olmos, “A base station assignment strategy for radio access networks with backhaul constraints”, ICT-MOBILESUMMIT 2008 Conference Proceedings, Paul Cunningham and Miriam Cunningham (EDS), IIMC International Information Management Corporation, 2008, ISBN: 978-1-905824-08-3, Stockholm - Sweden.

- "Final report on aroma algorithms and simulations results", AROMA Project Deliverable DR18, Editor(S): Jordi Perez-Romero, UPC. Authors list: Antunes, David (IST-TUL); Aparicio, Maite (TID); Audsin, Dev (KCL); Barbaresi, Andrea (TI); Casadevall, Fernando (UPC); Colonna, Massimo (TI); Correia, Luis M. (IST-TUL); Dahlén, Anders (TEL); Ferrús, Ramon (UPC); Fischer, Markus (PTIN); Galeana, Hiram (UPC); Garcia-Lozano, Mario (UPC); Gelabert, Xavier (UPC); Gomez, Alvaro (PTIN); Kuipers, Martijn (IST-TUL); Ljung, Richard (TEL); Ludovico, Michele (TI); Magnusson, Mats (TEL); Matamoros, Luis Miguel (TID); Monteiro, Joao (PTIN), Novillo, Francisco (UPC); Olmo, Joan J (UPC); d’ Orey, Pedro (PTIN); Sallent, Oriol (UPC); Sebastiao, Daniel (IST-TUL); Serrador, Antonio (IST-TUL); Vega, Avelina (TID); Vucevic, Nemanja (UPC); Wang, Lin (KCL); Zarba, Giovanna (TI).

Chapter 2. **State of the Art on OSA and WLAN Technologies**

In recent years, wireless local area networks (WLANs) have been widely deployed mainly in urban areas due to the ease of installation and the fact that operating in frequency bands does not require a license. This band has a limited number of channels and, in turn, is shared by other systems. The massive use of this band increases the levels of interference perceived by the receiving devices.

On the other hand, opportunistic spectrum access (OSA) is a technique based on mechanisms of cognitive radio that allows licensed spectrum to be opened to secondary users while limiting the interference perceived by primary users (licenses) [8]. Through this type of opportunistic access, it is possible to obtain a more efficient management of the radio spectrum.

Therefore, a combination of these two technologies would allow for an even more efficient use of licensed spectrum by allowing WLANs to use this spectrum in an opportunistic manner and, consequently, decongest the unlicensed band.

In this chapter, a brief description of the main concepts and characteristics of OSA and WLAN technologies is introduced, which will be used in the following chapters.

2.1 Dynamic Spectrum Access and Opportunistic Spectrum Access

The current spectrum management is based on static policies of access to the spectrum, but these policies are actually inefficient. Because of this, the Federal Communications Commission (FCC) proposed in [11] to change this spectrum management to a more versatile approach that fits the needs of modern wireless communications. These new polices of spectrum management are known as dynamic spectrum access (DSA) [8], [9]. DSA can be categorized in three different models. These models consider different conditions of time, space, use and ownership to access the spectrum. The models are shown in Figure 2.1 [8] and briefly discussed below.

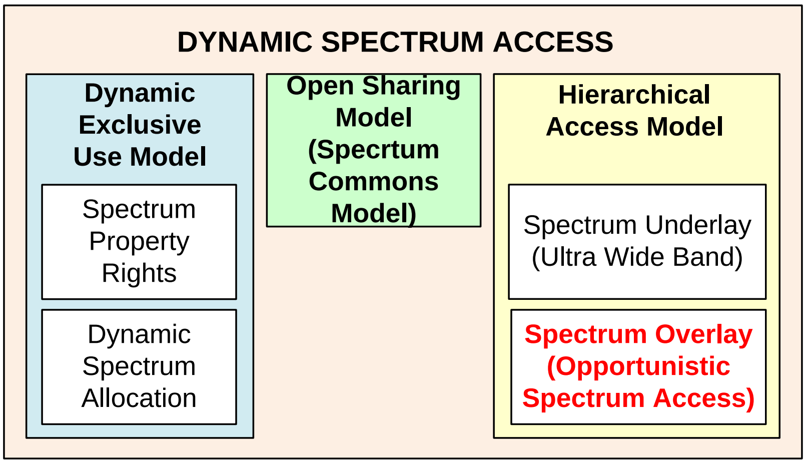


Figure 2.1: Taxonomy of dynamic spectrum access [8]

Dynamic Exclusive Use Model

This model relies on the concept of the current spectrum regulation policy which entitles its owner to exclusive rights to use that spectrum under certain rules. This model's purpose is to improve the spectrum efficiency by introducing flexibility in the spectral management. This model presents two trends: Spectrum property rights [17], [18] and dynamic spectrum allocation [19].

For the first one, licensees have the right to sell and trade spectrum and to freely choose technology. It should be noted that, although the licensees have the right to lease or share the spectrum for profit, such sharing is not mandated by the regulation policy. For instance, as suggested in [9], a service of IPTV-over-air combined with a cellular service could eventually be provided by a TV broadcast service operator.

The second trend was fueled by the European Drive Project [19], and its goal is for spectrum efficiency to be improved by means of a dynamic spectrum assignment, which exploits the spatial and temporal traffic statistics of different services. In other words, for certain points in space and time, only one operator has exclusive rights to the spectrum; however, the identity of the owner and the type of use can be changed.

Note that this model cannot eliminate white space (i.e. unused spectrum) in the spectrum resulting from the burst character of wireless traffic [8].

Open Sharing Model

This model is also known as spectrum common [9], [20], [21]. It uses open sharing among peer users as the basis for operating a spectral region and argues that radio spectrum is a public resource that should be equally accessible to everyone without undue government regulation.

Defenders of this model are supported by the success they have had with wireless services operating in the unlicensed industrial, scientific, and medical (ISM) radio band (e.g. WLAN). Centralized [22], [23] and distributed [24], [25] spectrum sharing strategies have been investigated to meet technological challenges under this spectrum administration model.

Hierarchical Access Model

This model explores the spectrum shared use by means of a hierarchical access arrangement that consists of primary and secondary users. In this way, a licensed band to a certain holder (primary user) can be opportunistically shared by one or multiple users (secondary users) that are currently operating in other bands (e.g. ISM band). Hence, secondary users can access the licensed spectrum while limiting the interference perceived by primary users (licensees). This model can be classified in two approaches: spectrum underlay and spectrum overlay.

Spectrum underlay*:* For this approach of spectrum shared use, the transmission power of the secondary user is very constrained so that secondary users are forced to operate at power levels below the noise floor expected by the primary users. These constrained power levels lead to the secondary users having to operate in short coverage areas, those which are adequate for operating as wireless personal area networks (WPAN) for connecting sensors or as a replacement for short length cabling [26].

A technology widely researched for the spectrum underlay is the well-known Ultra Wide Band (UWB) [27], [28]. In this technology, secondary users' transmissions are spread over a very wide spectrum band using low power, short length pulses. Consequently, this approach is not based on the detection of white space in the primary spectrum; therefore, it is possible for the secondary users to transmit in this band while the primary users are transmitting.

Spectrum overlay: This model is also known as OSA [8], [9], [29]. Unlike spectrum underlay, the transmission power of secondary users is not severely constrained; however, it is very important to identify when and where the secondary users are permitted to transmit. This model allows secondary users to opportunistically exploit local and instantaneous spectrum availability in a nonintrusive manner by considering spatial and temporal spectrum in the licensed spectrum.

In particular, this thesis is focused on the study of this type of hierarchical model. In the next sections, important concepts for the implementation of this model are described, which will be referred to as OSA from here on.

2.2 OSA Technology Enablers: Cognitive Radio

As mentioned above, this thesis focuses on the overlay approach under the hierarchical access model of dynamic spectrum access [9], [30]. This model was first proposed by Mitola [31], [32] under the term spectrum pooling and then explored by the DARPA Next Generation (xG) program [33] under the term OSA. The coexistence of secondary user networks with the primary user system was considered by Mitola`s works as long as a set of operations called a cognitive cycle [31] could be reliably implemented by secondary users.

Therefore, cognitive radio constitutes a much more comprehensive criterion, which can be applied to several circumstances of the radio communications networks, in order for such networks to improve their performance by implementing cognition techniques. Thus, OSA is considered an important application of cognitive radio that uses techniques of cognitive radio for operating.

As stated above, the key enabling technology of OSA techniques is cognitive radio (CR) technology, which provides the ability to share the wireless channel with licensed users in an opportunistic manner. A brief description of CR is denoted in the following section.

Cognitive radio consists of a radio system that can modify its transmitter parameters according to what is perceived from its environment [34]. CR devices have the properties of capability of cognitive capability and reconfigurability [35], [36] , unlike the conventional radio systems. The former is the capability to detect and obtain information from the surrounding environment. Reconfigurability consists of the ability to rapidly change the operational parameters according to the obtained information in order to achieve the optimal performance. The elements of the architecture of a cognitive radio network (CRN) are shown in Figure 2.2 and described below [37], [38].

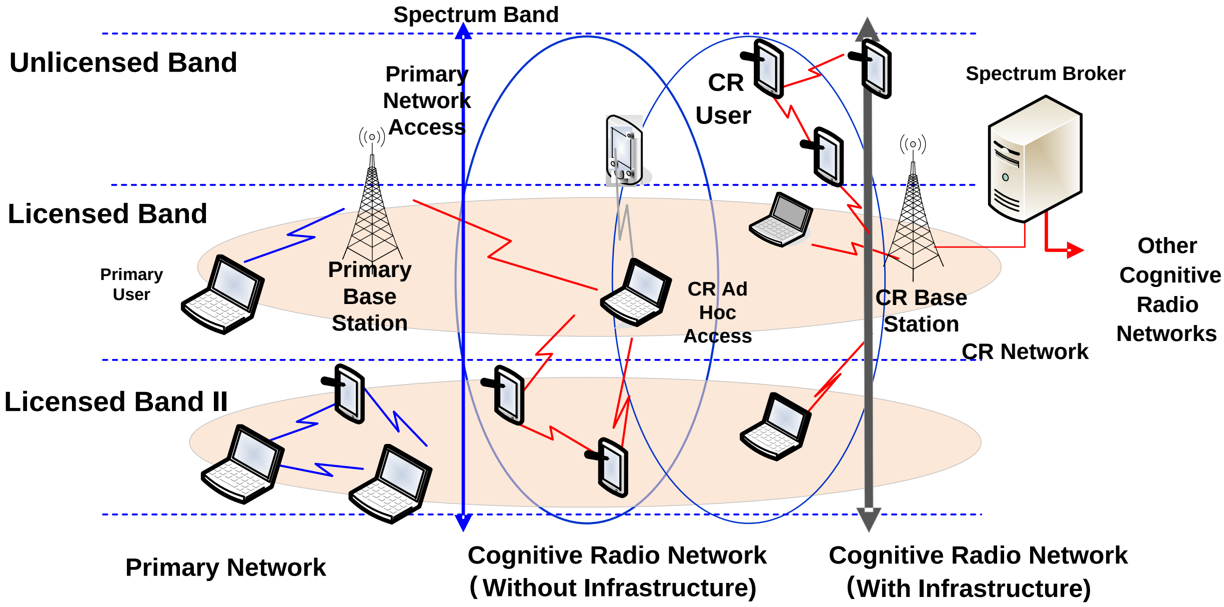


Figure 2.2: Cognitive Radio Network Architecture [37]

Network Components

The CR network architecture is composed of the primary network and the secondary network. In these types of networks, unused segments of licensed bands owned by the primary users (PU) can temporarily be utilized by secondary users (SU), despite the fact that the SUs don't have the spectrum usage rights [39], [40], [41].

The primary network (i.e. licensed network) is referred to as a set of primary users and one or more primary base stations, which are authorized to operate at a certain licensed spectrum band. These networks work in infrastructure mode, so that the base station controls the activities of the primary users. The operations of primary users should not be affected by unlicensed users because of priority in the spectrum access of primary users.

The secondary network (also called dynamic CR network, spectrum access network, or unlicensed network) does not have a license to operate in a desired band. Thus, SUs require complementary capabilities for sharing the licensed band. SUs can also be equipped with secondary base stations that provide single-hop connections to SUs.

Spectrum Heterogeneity

Spectrum heterogeneity is referred to as the capability of SUs to operate in both the unused segments of the licensed spectrum used by primary users and the unlicensed portions of the spectrum through wideband access technology. In this way, SUs have two types of operations: Licensed band operation and unlicensed band operation [42].

For the first one, primary users have priority for using the licensed band. Thus, in this band, secondary networks are dedicated to the detection of primary users. The channel capacity is based on the interference of nearby primary users. In such circumstances, the SUs must immediately stop using the licensed band and move to another segment of spectrum when PUs appear within the spectrum being used by SUs.

For unlicensed band operation, the right to access this band is the same for all SUs, since PUs are not operating in this band. Consequently, spectrum sharing techniques are needed in order for SUs to compete for access to the unlicensed band.

Network Heterogeneity

The secondary users have three different access types [36]: a. Secondary network access: where secondary users can be linked to their own secondary base station, on both licensed and unlicensed spectrum bands. b. Secondary ad hoc access: SUs have the capability of transferring information with other SUs through an ad hoc connection by using either licensed or unlicensed spectrum bands. c. Primary network access: By using primary band, SUs can access primary base stations.

Spectrum Management

As mentioned in Section 2.1.4, for secondary users to coexist with primary users, a set of operations needs to be implemented according to the cognitive cycle proposed in [31]. Based on this cycle, a new set of spectrum management functions are proposed for secondary network operation [36].

These functions allow secondary users to detect spectrum white space in the licensed band, select the best frequency bands, coordinate spectrum access with other users, and vacate the licensed frequency band when a primary user appears. The spectrum management process is supported by the following functions: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility. Figure 2.3shows a scheme of the proposed cognitive radio network management; the functions will be explained in the following sections.

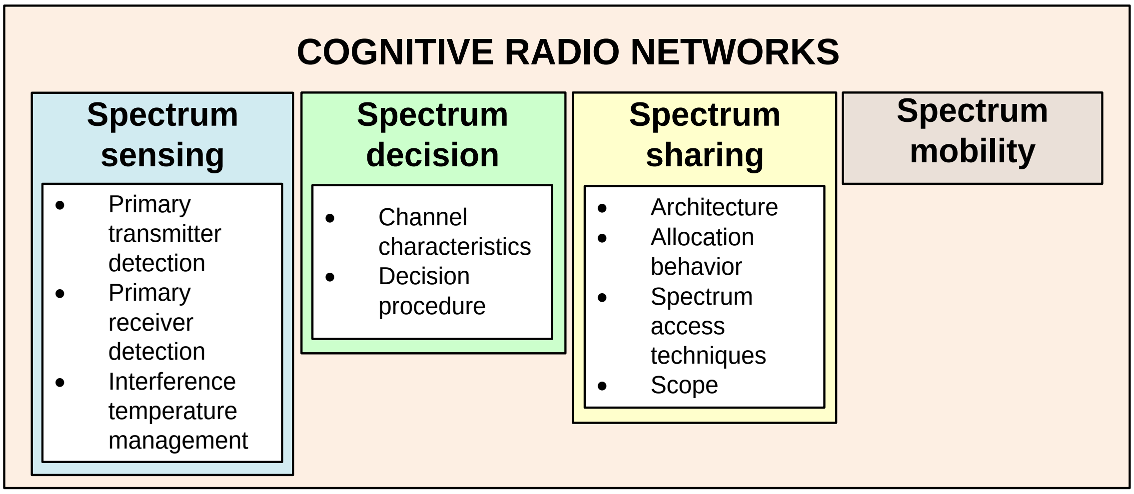


Figure 2.3: Cognitive Radio Network Management

Spectrum Sensing

Spectrum sensing allows the secondary user (CR user) to monitor its surrounding radio environment, catch the information referent to the available spectrum bands, and then detect spectrum holes. For this, each CR user is designed to be aware of and sensitive to the changes in its surroundings so that it can adjust its transmitting and receiving parameters, such as transmission power, frequency, modulation schemes, and etc. This fact allows the CR user to detect spectrum holes without causing interference to the primary network [36], [37], [38]. This technique can be classified in three groups: primary transmitter detection [43], [44], [45], primary receiver detection [46], and interference temperature management [34].

Spectrum Decision

Under the spectrum decision concept, CR networks have the capability to choose the best available spectrum in accordance with the QoS requirements of the applications. Spectrum decision is directly linked to the channel characteristics and operations of primary users. However, it can also be impacted by the operation of other secondary users in the network.

This function consists of two steps. In the first one, each white space is described taking into account both the time-varying radio environment and spectrum parameters, such as, for instance, the operating frequency and bandwidth. The second step consists of choosing the most appropriate spectrum considering the QoS requirements and spectrum descriptions [47], [48].

Spectrum Sharing

In cognitive radio networks, spectrum sharing is one of the major challenges for the open spectrum usage. Coexistence between secondary and primary users and the wide range of available spectrum are two important points in spectrum sharing. For this, spectrum sharing is performed while taking into account four aspects, which collect the shared nature of the wireless channels: the architecture, spectrum allocation behavior, spectrum access technique, and scope.

The architecture can be centralized or distributed. For the former, the spectrum allocation and access procedures are controlled by a central entity [23] whereas, for distributed architecture, the spectrum allocation and access are based on local (or possibly global) policies that are performed by each node distributively [29].

In relation to spectrum allocation behavior, the spectrum access can be cooperative or non-cooperative. For the first categorization, the interference measurements of each node are utilized, so that the effect of the communication of one node to other nodes is considered. For the non-cooperative spectrum, sharing only a single node is considered in non-cooperative so that interference in other CR nodes is not considered. Hence, non-cooperative solutions may result in reduced spectrum utilization [49].

The spectrum access technology is classified in overlay spectrum sharing and underlay spectrum sharing [50]. This classification has already been discussed in Section 2.1.3.

Finally, the scope of the spectrum sharing techniques is centered on two types of solutions: spectrum sharing within a CR network (intranet work spectrum sharing) and among multiple coexisting CR networks (internetwork spectrum sharing) [36].

Spectrum Mobility

In the cognitive process, a secondary user first captures the best available spectrum, and, from this spectrum, the secondary user then chooses the best channel as its new operating channel. In this context, if primary activity on the selected channel is present, then the user necessarily has to change its operating band [36].

Therefore, in cognitive networks, the spectrum mobility occurs when current channel conditions become worse or a primary user appears. Also, spectrum mobility gives rise to a new type of handoff in cognitive networks that is referred to as spectrum handoff [37].

2.3 OSA in TV White Space

OSA is a spectrum sharing technique, which enables the unlicensed use of the unused segments of a licensed spectrum bands without affecting the primary users [52]. These unused spectrum segments are also known as white spaces (WS) or spectrum holes (SH) [37], [51].

Several research works have exposed the fact that certain segments of electromagnetic spectrum are not efficiently used, in particular, those corresponding to TV broadcast services, i.e. within certain geographical areas, some TV channels are not being utilized [53], [54]. These unused portions of TV spectrum are called TV White Space (TVWS) and are being considered by regulatory entities as potential solutions to spectrum scarcity.

In the United States, TV broadcasting operates in VHF and UHF bands of the electromagnetic spectrum by using a channel bandwidth of 6MHZ. In particular, it uses four frequency bands: 54-72MHz, 76-88MHz, 174-216MHz and 470-698MHz and is regulated by the FCC [56]. Instead, for Europe, the TV white spaces are located in the 470-790MHz contiguous frequency bands, and each channel occupies an 8MHz band. In general, for TV, the usage rules are regulated by the ECC.

Nowadays, the ECC [55] and the FCC [56] have each adopted important measures for carrying out the cognitive access to TV white spaces. So, for instance, the two entities have different viewpoints as to how to protect the existing services while harvesting the available spectrum in TV white spaces. Also, the protection based on distance is required by the FCC, while the ECC is focused on secondary power control. However, secondary spectrum access technologies such as geo-location with databases or sensing are used by both regulators.

2.3.1 Cognitive Mechanisms to Access White Spaces

Opportunistic access to white spectrum space by secondary users comprehends the detection of the available spectrum holes in licensed bands (e.g. TV bands) and the use of that spectrum based on the guidelines established by the regulator, whose main objective is to protect primary users from harmful interferences.

To find WS, secondary users could use several cognitive mechanisms that have already been proposed by some regulatory entities [52], [55], [56]. These are: geo-location with databases, spectrum sensing and beacons. The first two mechanisms have been recognized as the main technologies for opportunistic access to TV bands [55], [56], [57]. However, nowadays, the geo-location assisted by the database is considered, in the short term, to be the most favorable solution for the detection and avoidance of interference spectrum holders. Spectrum sensing has already been discussed in previous sections.

Geo-location Databases: In this method, secondary users consult a centralized geo-location database to establish if there is any available TVWS in their surrounding area, which can be used without causing interference to other services [59] .

Figure 2.4 shows a functional scheme proposed by [58] for accessing white spaces based on geo-location. A master secondary user consults a list of databases provided by the regulator (1, 2). Then, this device chooses a database from this list and sends to it several parameters describing its location and device attributes (3). Thus, the database responds with the details of the frequencies and power levels it is allowed to use (4).

Still, some important parameters have been defined, such as the location precision, the frequency with which devices must connect to the database, and the characteristics of the database itself. Note that, if a more exact location is required, it leads to unnecessary complexity for the secondary users, and additionally, given the continuous contact with the database, the battery life time is diminished.

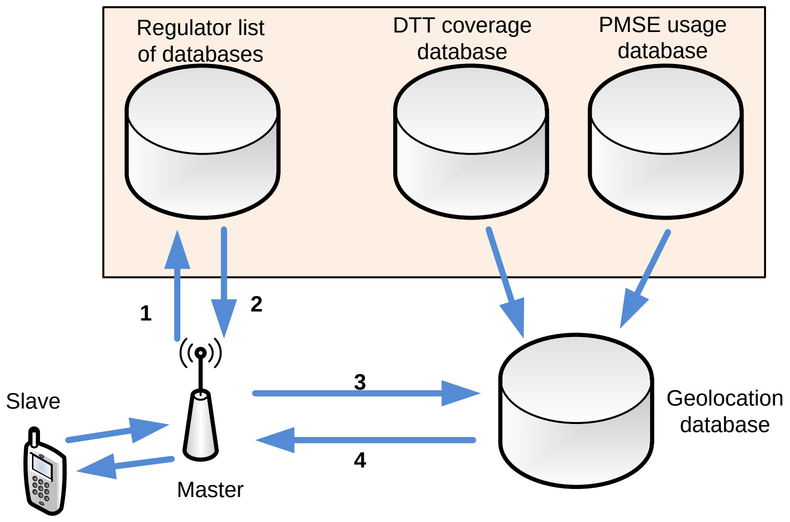


Figure 2.4: Functional Scheme for Accessing to White Spaces [58]

Beacons: Another mechanism used for detecting white space in the spectrum is by using beacon signals. With this mechanism, the secondary users can only transmit on a channel if they have previously received the beacon signal with information about whether the channel is available. Beacon signals can be transmitted by TV stations or a secondary transmitter operating in unlicensed TV bands. This mechanism requires a dedicated infrastructure for emitting beacon signals, which are operated by the spectrum holder [51], [56].

2.4 Initiatives for OSA Standardization

Nowadays, the applicability of the OSA model is being investigated in many different contexts [52]. Several activities have been carried out on the usage of TVWS. For instance, the IEEE 802.11af standard has been proposed for operating in scenarios with short range wireless access over TVWS. This standard is known also as White-fi, in allusion to the use of Wi-Fi technology within TV White spaces using cognitive radio technology. For the usage of TVWS by IEEE 802.11af devices, it is required that they do not cause interference to the primary users. The IEEE 802.11af working group is responsible for defining a standard for implementing this (started in 2010 and still in draft) [60].

Taking that into account, the 802.11af devices will operate on frequencies below 1GHz (i.e. TVWS). This fact improves the propagation characteristics, since the signals are easily absorbed when compared to 802.11 traditional-that operates in 2.4GHz. In this way, greater coverage range of the transmitted signals can be obtained. For providing data throughput rates similar to those reached by Wi-Fi technologies, it will be necessary to aggregate several TV channels. The map of available primary channels is obtained by a geo-location database control [60].

Another proposal more focused on Internet and whole-home networks is the ECMA-392 standard proposed by Cognitive Networking Alliance (CogNeA) and initiated in 2008. This standard defines physical and medium access control layers for operating in TVWS. This standard is designed for applications such as high speed video streaming and Internet access on personal/portable electronics, home electronics equipment and computers and peripherals [61].

The first standard that was developed by fully incorporating the concept of CR as well as the first CR-related air interface standard is the IEEE 802.22 (finalized in 2011), also called standard for Wireless Regional Area Networks (WRANs). This one is designed to operate over available UHF/VHF TV bands between 54 and 862 MHz (scalable to 41-910 MHz), but only frequencies below 698 MHz will be allowed by the FCC regulations in the US. The channel bandwidths used by this standard include 6 MHz, 7 MHz and 8 MHz compatible with various TV standards around the world [62], [63], [64].

With the purpose of improving the coexistence mechanisms for license-exempt operation, the IEEE 802.16h standard was created. This standard was started for unlicensed bands, with a focus on 3.65 GHz and then migrated to TVWS. The target of this one is to use intelligent technology to let several systems share resources, so that coexistence among license-exempt systems based on IEEE 802.16 is allowed in order to satisfy QoS requirements of IEEE 802.16 standard [62].

2.5 Wireless Local Area Networks (WLANs)

The predominant technology used in WLAN is based on the specifications of IEEE 802.11 developed by the Institute of Electrical and Electronics Engineers (IEEE) LAN/MAN Standards Committee (IEEE 802) and is commonly referred to as Wi-Fi. Wi-Fi is a trademark of the Wi-Fi Alliance, the trade organization that tests and certifies that it meets the IEEE 802.11x. IEEE 802.11 is defined within the protocol architecture developed as an IEEE 802 standard, consisting of three layers: logical link control (LLC), media access control (MAC) and physical [65].

The IEEE 802.11 standard was approved in 1997 and designed to operate in a 2.4 GHz Industrial Scientific and Medial (ISM) frequency band, with data rates of 1 Mbps. ISM bands are shared by a variety of other systems, but no license is required for operation within these frequencies. This makes them ideal for a general system for widespread use. Then, in 1999, the first WLAN standard IEEE 802.11-based denominated 802.11b was approved. This one operates with data rates of 11 Mbps using a modulation scheme known as Direct-Sequence Spread Spectrum (DSSS). Parallel to this standard, the 802.11a was developed. This one employs the 5 GHz ISM band, provides data rates of 54 Mbps, and uses a different modulation technique scheme known as Orthogonal Frequency Division Multiplexing (OFDM) [65], [66].

Several variants have been developed from the two standards. Table 2.1 shows an overview of these developments. However, of the two standards, the 802.11b variants are currently the predominant in the WLAN market, because the chips for the lower 2.4 GHz band are easier and cheaper to manufacture [67]. Hence, the studies conducted in this thesis focus on the 2.4 GHZ ISM band.

Table 2.1: Summary of the Main 802.11 Standards

	802.11	**802.11b**	**802.11a**	**802.11g**	**802.11n**
Date of standard approval	1997	1999	1999	2003	2009
Maximum data rate (Mbps)	1,2	11	54	54	600
Modulation	DSSS	DSSS	OFDM	DSSS, OFDM	DSSS, OFDM
RF Band (GHz)	2.4	2.4	5	2.4	2.4, 5
Channel width (MHz)	20	20	20	20	20, 40

2.5.1 Components and Architecture

Next, the main components and architecture of WLANs based on IEEE 802.11 standards are described.

Station (STA): For wired LANs, an address usually corresponds to a physical location, but this is not always the same for WLANs. Considering the IEEE 802.11standard, the addressable unit is referred to as a station (STA). In this context, an STA denotes no more than the origin and/or destination of a message. In other words, STA is a logical entity that is a singly addressable instance of a medium access control and physical layer interface to the wireless medium [66].

An access point (AP) refers to an entity that includes a station (STA) and gives access to the distribution services through the wireless medium for associated STAs.

The architecture of IEEE 802.11 is composed of several components interacting to provide a WLAN that supports the STA mobility transparently to the upper layers. The basic building block of an IEEE 802.11 LAN is denominated as a basic service set (BSS). Figure 2.5a shows one BSS composed of three STAs. From the figure, the ovals are used to describe a BSS as the coverage area within which the member STAs of the BSS can maintain communication.

An independent BSS or IBSS is referred to as the most basic form of association where stations can directly communicate with one another in an ad-hoc network. For instance, from Figure 2.5a, BSS_1 can be considered as an IBSS.

Considering this, a set of stations associate with an access point dedicated to managing the BSS. In this context, a BSS built around an AP is known as an infrastructure BSS and is represented by BSS_2 and BSS_3 in Figure 2.5b. Infrastructure BSSs may be interconnected via their APs by means of a distribution system (DS). The BSSs interconnected through a DS are denoted as an extended service set (ESS) [66], [67].

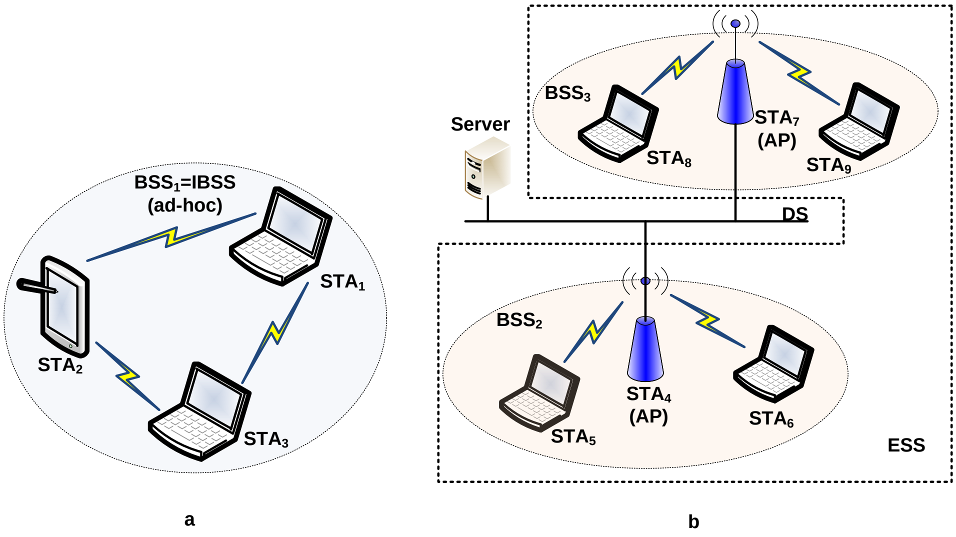


Figure 2.5: IEEE 802.11 Components and Architecture

2.6 WLAN Spectrum Management

2.6.1 Channels Description

As mentioned previously, WLANs are based on the IEEE 802.11 standard and operate in the ISM bands. These bands are defined in Table 2.2 [68].

Table 2.2: ISM Bands

Band	Range
900 MHz	902 to 928 MHz
2.4 GHz	2.4 to 2.4835 GHz
5 GHz	5.15 to 5.35 and 5.725 to 5.825 GHz

These band segments demonstrate different behaviors. For instance, lower frequencies have better coverage range, but the bandwidth is limited and, therefore, has lower data rates. On the other hand, the higher frequencies present less coverage range and are subject to greater attenuation from solid objects.

IEEE 802.11 standard establishes fourteen channels for operating in a 2.4 GHz ISM band. The number of available channels is not the same in every country. It depends on the spectrum allocations in each country and the different requirements established by the regulatory authorities. Table 2.3 provides a list of the available channels for some countries. So, for instance, in the United States, 11 channels are allowed by the FCC, while, in Europe, the ETSI establishes 13 channels for use [66].

Also, the 802.11 WLAN standards specify that these channels be 5 MHz apart from each other (except for the last two channels with 12 MHz of separation) and a bandwidth of 22 MHz, indicated as 20MHz in

[3]. Hence, considering these bandwidth and channel separations, the adjacent channels overlap, so that if devices are transmitting on adjacent channels, these will interfere with each other. Table 2.4 provides the frequencies assigned for each channel [66].

Given the overlapping between channels, the maximum number of non-overlapping channels is three. Figure 2.6 shows the five combinations of available non-overlapping channels which can be obtained in the 2.4 ISM band. From this figure, the sets of non-overlapping channels can be 1, 6, 11, or 2, 7, 12, or 3, 8, 13 or 4, 9, 14 (if allowed) or 5, 10 (and possibly 14 if allowed).

The IEEE 802.11 specification also defines a spectral mask which describes the permitted power distribution across each channel, so that the transmitted energy by any transmitter must fall within the levels defined by the mask. Spectral mask is defined as the energy from the transmitter that will extend beyond the 22 MHz channels allocated (i.e. +/- 11 MHz from the center frequency). Hence, this one establishes the maximum energy levels that the transmitter can emit on a given spectrum. At 11 MHz from the center of the channel, the energy must be 30 dB lower than the maximum signal level, and at 22 MHz away, the energy must be 50 dB below the maximum level. Note that, further away from the center frequency, the energy levels fall further; however, certain energy is still present and could cause interference on some channels [66], [67], [68].

Table 2.3: Available Channels per Country

Channel Number	United Stated (FCC)	Europe (ETSI)	Japan
1	Yes	Yes	Yes
2	Yes	Yes	Yes
3	Yes	Yes	Yes
4	Yes	Yes	Yes
5	Yes	Yes	Yes
6	Yes	Yes	Yes
7	Yes	Yes	Yes
8	Yes	Yes	Yes
9	Yes	Yes	Yes
10	Yes	Yes	Yes
11	Yes	Yes	Yes
12	No	Yes	Yes
13	No	Yes	Yes
14	No	No	802.11 b

Table 2.4: Frequency Channel Plan

Channel Number	Lower Frequency MHz	Center Frequency MHz	Upper Frequency MHz
1	2401	2412	2423
2	2404	2417	2428
3	2411	2422	2433
4	2416	2427	2438
5	2421	2432	2443
6	2426	2437	2448
7	2431	2442	2453
8	2436	2447	2458
9	2441	2452	2463
10	2451	2457	2468
11	2451	2462	2473
12	2456	2467	2478
13	2461	2472	2483
14	2473	2484	2495

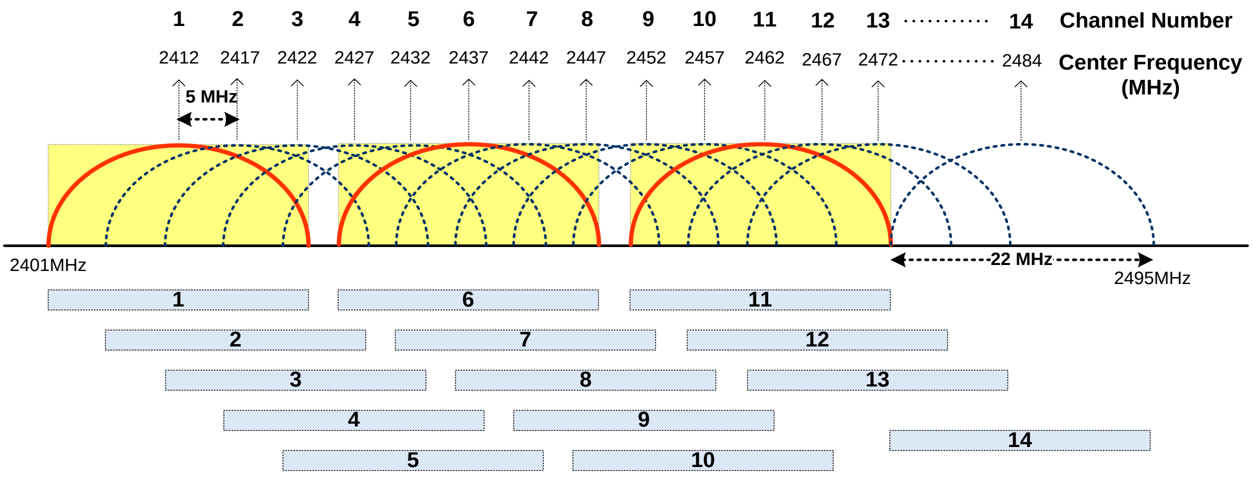


Figure 2.6: WLAN Overlapping Channels

2.7 Channel Assignment Schemes

This section provides a brief summary of several mechanisms that have been proposed by the research community for solving the problem of channel assignment in 802.11-based WLANs.

In the last several years, the deployments of 802.11-based WLANs have had a high increase, especially in urban zones. This fact can cause performance problems in the wireless networks, especially by congestion of the ISM band, so it is necessary to have mechanisms that can help improve their performance. Channel assignment technique is one of the main mechanisms to consider for improving the WLANs performance. This consists of a frequency channel being assigned to each AP for its use.

Deployments of WLANs can be categorized as coordinated or uncoordinated, in accordance with the way in which they are managed [7]:

For coordinated deployments, the environment information from WLANs (i.e. APs and STAs) can be entirely monitored and managed by a central entity. In this context, said entity may perform the mechanisms for solving the channel assignment problem. This solution approach is known as centralized computing. Some examples are WLANs deployment in university campus, airports, or mesh networks.

On the other hand, for uncoordinated deployments, WLANs operate in the absence of a central control, so that each AP in the network scenario only knows its own environment information, and not that of the other APs, and vice versa [69]. In such circumstances, any mechanism for solving the channel assignment problem can only be performed by each AP. This solution approach is called distributed computing. An example for this case could be the deployment of WLANs done by different telecommunications operators. Nevertheless, it is noteworthy that the APs deployed in a coordinated deployment could also be capable of running distributed computing. In Figure 2.7, a scheme which describes the relation between the previously mentioned concepts is depicted.

Also, there are other techniques used for mitigating network performance problems, such as, for instance, for coordinated deployments, a typical technique is what is known as association control or load balancing, in which a main unit associates the STAs with the APs with the purpose of balancing traffic in each network [70]. On the other hand, for uncoordinated deployments, the power control - in which transmission power is dynamically tuned [71], [72], or careful carrier-sensing - where unnecessary carrier sensing is avoided - [73] is used. However, this section is focused on channel assignment techniques, since, in the next chapters, several proposals for solving the channel assignment problem are developed.

Another aspect to consider is whether the channel assignment is static or dynamic [7]: The former refers to the channel assignment for the initial deployment of WLANs. Dynamic channel assignment consists of the channel reassignment or adjustment for WLANs.

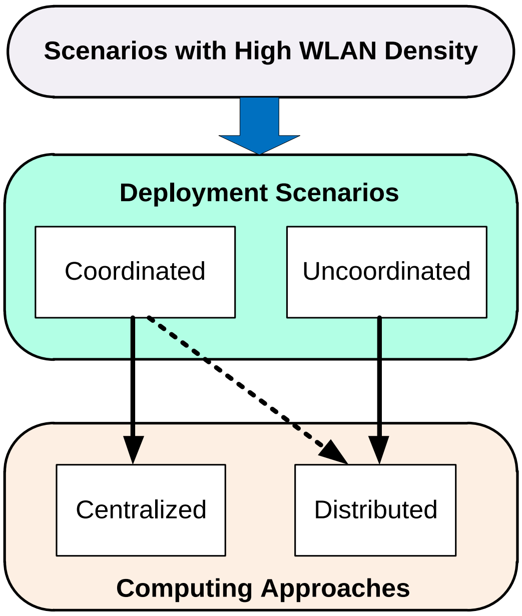


Figure 2.7: WLAN Deployments

Next, several techniques are briefly exposed. These are based on the concepts mentioned above.

Optimization techniques are implemented in order to obtain optimal solutions for the channel assignment problem in WLAN deployments. Integer linear programming (ILP) is a class of mathematical techniques for solving general optimization problems. This is frequently used in resource assignment problems [74], [75]. Algorithms to optimally solve this optimization problem exist (e.g. branch and bound algorithms) [76], but they are not efficient for a large number of APs, given that these require high computational efforts [77]. In practice, the optimal results are used as a benchmark for other solutions with a lower computational complex. These can be categorized as coordinated, centralized and static techniques.

In [4], the channel assignment problem is formulated as an integer linear programming (ILP) problem. The authors propose an ILP problem that aims to minimize the amount of client traffic disruption due to a new assignment process, while maintaining the resulting channel utilization below that of the previous assignment.

Likewise, in [7], the channel assignment is conceived as an ILP problem. This is formulated to fulfill certain interference constraints (i.e. optimization objective is not implemented), which lead to the maintenance of the interference among APs below a certain threshold and assign only one channel to each AP.

Also, for an opportunistic environment such as the one proposed in [16], the authors address the problem formulated as an ILP problem whose constraints balance the network load in the two bands (i.e. considering an opportunistic scenario) and also allocate the channels for the secondary users within a mesh network. In other opportunistic works, such as [81] and [82]; the authors formulate the channel assignment problem as a non-integer linear programming problem (i.e. variables, objective function and constraints are not linear) in order to maximize the utilization of the spectrum by considering an opportunistic scenario. Additionally, both works consider non-overlapping among channels and do not contemplate spectrum heterogeneity and channel prioritization.

Hence, taking into account the aforementioned computational problems, the channel assignment problem can be solved with short execution times by means of several heuristic algorithms based on well-known resource assignment techniques [7].

Heuristic algorithms based on graph coloring techniques are often used for channel assignment [83], where the network is represented as a graph composed by vertices and edges. APs are vertices, edges between APs represent the interference between APs and colors refer to the channels.

Thus, in [5], following the same target as for the previously mentioned ILP problem the authors propose two heuristic channel assignment algorithms. These are based on building a Minimum Spanning Tree (MST) of the network graph. In this work, the overlapping between channels is considered. Accordingly, this technique needs to know environment information from all APs to be considered as coordinated, static and centralized.

Authors in [6] use the well-known DSATUR (Degree of Saturation) algorithm, which is widely utilized by the research community for solving the channel assignment problem in legacy WLANs, introduced by Brélaz [84]. It is based on the concept of a saturation degree (i.e. the number of differently colored neighbors of a vertex). The fundamental idea of this algorithm is to choose the vertex with the highest saturation degree and color it with the first color on the list of admissible colors for each iteration. The list of admissible colors is determined according to the coloring problem statement. In particular, in [6], the channels are considered without overlapping, so that, given a set of colors, the colors that color the neighboring vertices of a certain vertex are considered inadmissible.

This algorithm could be applied at any AP in a dynamic way, but given that the construction of the graph is need for the channel assignment, cooperation protocols such as the Inter-AP Protocol (IAPP) [78] would have to be used by the APs. In this way, this technique could be assumed as distributed and uncoordinated. Note that, it can also be implemented by a central entity. Other works on DSATUR have been presented in [79] and [80].

In [85] and [86], the LCCS (Least Congested Channel Search) algorithm is proposed and implemented respectively, in which an AP chooses to operate on the channel with the least number of associated clients. Note that each client associated with a certain channel is linked to another AP. Another technique is known as Hminmax, which is defined and developed in [86], in which an AP computes for each available channel the maximum interference that it would have with its neighbors and chooses the channel with the minimum value of maximum interference. These algorithms can be considered as dynamic, distributed and uncoordinated.

Simulated annealing (SA) is a probabilistic meta-heuristic for the global optimization problem of finding a good approximation for the global optimum of a certain function in a large search space [87]. In [88], the authors present a distributed version of SA for solving the dynamic channel assignment problem in High-Density WLANs. The objective is to find a proper channel assignment, such that the total interference is minimized.

To provide a qualitative comparison among different schemes in terms of algorithm execution, behaviors, complexity and scalability in the context of channel assignments in WLAN considering only ISM channels, the reader is referred to [7].

A comprehensive revision of the models and methods that the literature provides on the channel assignment mechanisms in wireless systems can be checked in [89]. In this work, the authors present a broad description of the practical settings in which frequency assignment is applied, as well as a classification of the different models and formulations described in the literature, such that the common features of the models are emphasized.

Also, a survey on the channel assignment problem in wireless networks including those with opportunistic access can be found in [90]. The authors present a discussion on the various challenges and approaches that have been used by different researchers to solve the problem of channel assignment considering different interference issues and efficient utilization of available communication channels for wireless system environment and cognitive radio based networks.

Chapter 3. Spectrum Availability in Indoor Locations for Opportunistic Spectrum Access in Dense Urban Scenarios

3.1 Introduction

As mentioned in Chapter 2, the inefficient use of licensed spectrum has led to the existence of spectrum holes (i.e., spatial locations and time intervals where a given band is not occupied) in certain areas. On the other hand, the probability that short-range communications systems can use spectrum holes from licensed bands is high due to the limited transmission ranges of such potential secondary users. Because of this, the primary users would be less exposed to interference from the SUs.

Hence, in this chapter, the possibility to exploit OSA for secondary short-range radio communications systems within indoor locations in dense urban areas is analyzed where a primary system is assumed to provide outdoor coverage. In particular, the main contribution of the thesis is the quantification of the reusable area (i.e., spatial spectrum availability) inside the buildings located in the service area of a given primary system.

The spatial reusability conditions are established based on the level of interference that the primary receiver can tolerate from a secondary transmitter as well as the level of interference experienced by the secondary receiver due to primary transmissions.

Existing works have already addressed the computation of the spectral availability for secondary systems [42], [91], focusing mainly on the impact of using directional antennas in a single primary communication link. In our analysis, a more detailed characterization of outdoor, indoor and building penetration losses has been incorporated, and results are given for typical deployment configurations of the primary system in a dense urban scenario. A recent study exposed in [92] has determined the TVWS in Europe and has compared them with those obtained in the US. This study was done by considering the available white space opportunities in 11 European countries. It considers two scenarios in which the percentage of overall average availability of the TV channels for the entire evaluated European region by area is considered: the first one consists of a scenario in which the use of adjacent channel usage is unrestricted so that the obtained result is 56%. For the second scenario, the resulting value is 25%.

This chapter is organized as follows. Section 3.2 describes the main general aspects of the type of scenarios under study. In Section 3.3, the system model and assumptions considered for assessing spectrum reuse are introduced. Then, in Section 3.4, conditions for the computation of the reusable area and considered propagation models are discussed. Results are provided in Section 3.5 and, finally, concluding remarks are mentioned in Section 3.6.

3.2 Scenario Description

In this study, two cases of extreme scenarios are proposed to be analyzed, as shown in Figure 3.1.

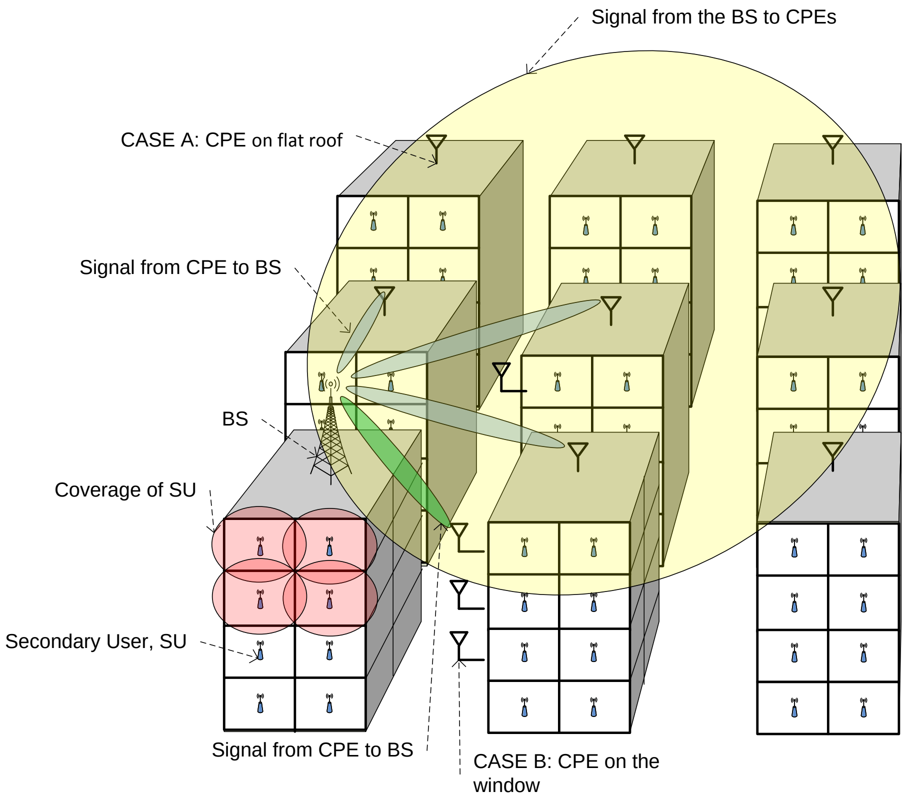


Figure 3.1: Scenario Under Consideration

This is an urban scenario with a high density of buildings with various floors and where a high utilization of the wireless spectrum may be expected because of the important concentration of multiple and different wireless communications systems. In our analysis, we rely on a Manhattan model to account for a typical building layout; this model is commonly used for describing propagation models in urban scenarios [93].

Then, in this scenario, we consider the co-existence of primary and secondary wireless communications systems. The former are assumed to provide outdoor coverage through the use of base stations *(BS)* installed on the roofs of the buildings and customer premise equipment *(CPE)* with directional antennas placed either on flat roofs or on the outside walls of the buildings and half-duplex communication(e.g., Local Multipoint Distribution Systems, fixed WiMAX solutions) [94].

As for secondary systems, we consider short range wireless communications intended to be used within the building (e.g., residential or enterprise WLAN networks), and each device is denoted as a secondary user (*SU*). In this particular study, for the sake of simplicity, it is considered that primary and secondary systems use the same transmission mask and channelization as those described for WLANs in Chapter 2.

3.3 System Model

In this section, we discuss the system model used to quantify spectrum reusability in the aforementioned types of scenarios.

3.3.1 Conditions of Spectrum Reuse

The conditions for determining spectrum reusability are formulated in terms of the interference levels allowed in both primary and secondary receivers, so that the secondary users can reuse the primary frequency band without disturbing the primary system or being disturbed.

Hence, as shown in Figure 3.2, an SU can use a given primary channel whenever the interference received by any PU receiver tuned to that channel, $I_{SU \to PU}$, is below the PU receiver sensitivity S_{PU} minus a given protection margin M_{PU}. This usage condition imposed on SU transmitters can be formulated as:

$$I_{SU \to PU} = S_{PU} - M_{PU} \tag{3.1}$$

Additionally, the successful operation of SU receivers tuned into primary channels also requires the interference received from PU transmitters, $I_{PU \to SU}$, to be lower than SU receiver sensitivity S_{SU} minus a protection margin of M_{SU}. Hence, the usage condition required by SU receivers can be formulated as:

$$I_{PU \to SU} \leq S_{SU} - M_{SU} \tag{3.2}$$

It is worth noting that, in both cases, the receiver protection margins are formed according to the following expression:

$$M_x = M_{SH-x} + M_{I-x} \tag{3.3}$$

where, $M_{SH\text{-}x}$ is the shadowing margin, $M_{I\text{-}x}$ corresponds to the interference margin, and x is either PU or SU. These represent the loss propagation in the receiver due to shadowing from obstacles (e.g. buildings) affecting the wave propagation, or by other devices using the same or adjacent channels, respectively.

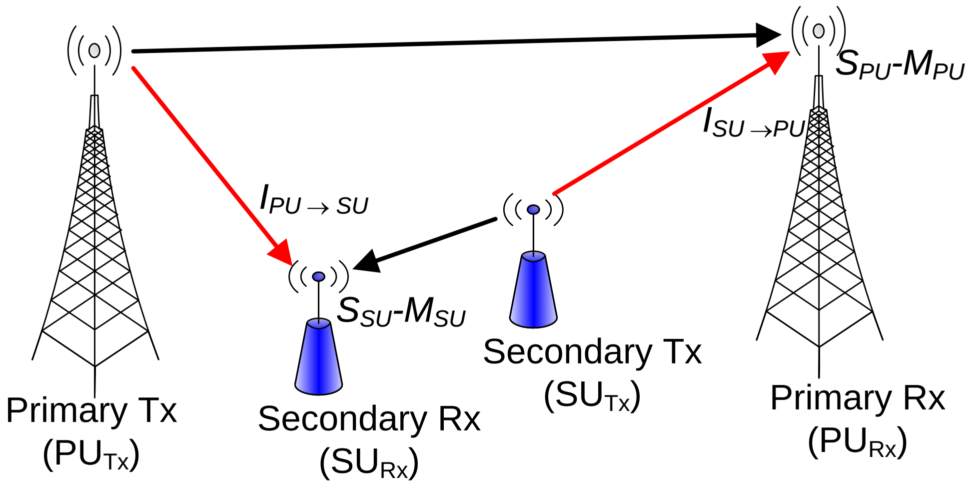


Figure 3.2 : Interference characterization for spectrum reuse.

3.3.2 Primary System Characterization

We consider a point-to-multipoint primary system where BSs are located at the tops of buildings. Concerning the location of CPEs, two different cases are analyzed (see Figure 3.1):

- Case A: CPEs are also installed on the flat roofs of the buildings and LOS (Line-of-Sight) to the BSs is required.
- Case B: CPEs are installed below building roofs on external walls or windows of the buildings. In this case Non LOS operation is considered.

Directional antennas are considered in both cases and the transmission power is dimensioned according to typical link budget parameters considered for 802.16 systems [42]. Accordingly, the BS transmission power P_{BS} is calculated as follows:

$$P_{BS} = S_{CPE} + L_{(BS-CPE)} - G_{BS} - F_{BS}(\theta) - G_{CPE} - F_{CPE}(\theta) + M_{SH} \quad (3.4)$$

where S_{CPE} is the sensibility of a CPE, $L_{(BS\text{-}CPE)}$ is the propagation loss between the BS and the considered CPE, G_{BS} and G_{CPE} are, respectively, the BS and CPE antenna gains, $F_{BS}(\theta)$ and $F_{CPE}(\theta)$ are, respectively, the BS and CPE antenna responses with respect to the azimuth angle θ and M_{SH} is the shadowing margin. Analogously, the transmitted power of a given CPE, P_{CPE}, is given by:

$$P_{CPE} \geq S_{BS} + L_{(CPE-BS)} - G_{CPE} - F_{CPE}(\theta) - G_{BS} - F_{BS}(\theta) + M_{SH} \quad (3.5)$$

3.3.3 Secondary System Characterization

As for secondary systems, we consider short range radio communication devices. The type of antennas used in these environments is omnidirectional, and it is assumed that secondary devices always transmit at their maximum power level. Hence, the SU transmission power is not computed in this work, so that such secondary systems are characterized under such conditions and typical transmission parameters (transmission power, sensitivity) for 802.11 systems [42].

3.4 Computation of the Reusable Area

We define the reusable area as the set of locations inside the buildings where secondary devices would be able to successfully use the primary spectrum. Accordingly, next, we describe the necessary conditions for computing the reusable areas as well as the propagation models used in the proposed cases.

3.4.1 Calculation of the Reusable Area

The computation of the reusable area is done by developing the two basic conditions stated in Section 3.3.1 for spectrum reuse in all indoor locations of the considered scenario. Hence, a location belongs to the reusable service area if the following four conditions are fulfilled:

C_1: Condition intended to assert whether the interference from primary BS to secondary users (I_1) is tolerable:

$$I_1 \triangleq P_{BS} + G_{BS} + F_{BS}(\theta) - L_p + G_{SU} + F_{SU}(\theta) \leq S_{SU} - M_{SU} \quad (3.6)$$

where, L_P is the propagation loss, G_{SU} is the SU antenna gains, $F_{SU}(\theta)$ is the SU antenna responses with respect to the azimuth angle θ, S_{SU} is the sensibility of a SU, M_{SU} is the secondary receiver protection margin.

C_2: Condition intended to assert whether the interference from primary CPEs to secondary users (I_2) is tolerable:

$$I_2 \triangleq P_{CPE} + G_{CPE} + F_{CPE}(\theta) - L_p + G_{SU} + F_{SU}(\theta) \leq S_{SU} - M_{SU} \quad (3.7)$$

C_3: Condition intended to assert whether the interference from secondary users to primary BS (I_3) is tolerable:

$$I_3 \triangleq P_{SU} + G_{SU} + F_{SU}(\theta) - L_p + G_{BS} + F_{BS}(\theta) \leq S_{BS} - M_{BS} \quad (3.8)$$

where, P_{SU} is the SU transmission power.

C_4: Condition intended to assert whether the interference from secondary users to primary CPEs (I_4) is tolerable (?):

$$I_4 \triangleq P_{SU} + G_{SU} + F_{SU}(\theta) - L_p + G_{CPE} + F_{CPE}(\theta) \leq S_{CPE} - M_{CPE} \quad (3.9)$$

The four conditions are checked in all indoor locations of the scenario under study. As for mathematical notation, each indoor location is named as $u_{i,}$ and the reusability condition in that location attending only to interference condition C_j is defined by:

$$RA_j(u_i) = \begin{cases} 1 & ; C_j \text{ is true} \\ 0 & ; \text{otherwise} \end{cases} \quad (3.10)$$

Hence, in a scenario with U indoor locations, the percentage of reusable area attending to a given interference condition C_j is denoted as RA_j and computed as:

$$RA_j(\%) = \frac{1}{U}\sum_{i=1}^{U} RA_j(u_i) \qquad i = 1,...,U \tag{3.11}$$

Finally, the percentage of the reusable area accounting for all interference conditions is obtained by:

$$RA(\%) = \frac{1}{U}\sum_{i=1}^{U}\left(\prod_{j=1}^{4} RA_j(u_i)\right) \qquad i = 1,...,U \tag{3.12}$$

3.4.2 Propagation Models

Figure 3.3 shows the different radio propagation cases arising in the considered scenarios for the computation of either interference or received power. For this, we need to measure propagation loss in outdoor, indoor and building penetration scenarios.

Next, propagation models considered for each case are discussed in detail.

3.4.2.1 Building Penetration Losses

The propagation model used to calculate the path loss between a transmitter located in the external part of a building and a receiver inside a room in another building [95], or vice versa, is given by the following expression:

$$L_{bp} = L_{outside} + W_e + W_{ge} + \max(W_i\, p, \alpha d_w) - hG_h \tag{3.13}$$

where $L_{outside}$ is the loss from an external transmitter to the external part of the wall of any building, it is described in the following section, W_e is the loss in the externally illuminated wall (considering a penetration angle ϕ = 90°), W_{ge} is the additional loss in the external wall for ϕ= 0°. W_i is the loss in the internal walls and p is the number of internal walls, α is the loss per distance between adjacent walls and d_w is the distance between walls, h is the height above the outdoor reference path loss level, and finally G_h is the height gain. This model is used to compute the propagation loss L_p of the interferences defined in (3.6), (3.7), (3.8) and (3.9). It is worth noting that the application of this model is done considering that the transmitters and the receivers are in different buildings.

3.4.2.2 Outside Propagation Model

Using the model described in [96], we calculate the propagation loss between a transmitter and a receiver with different antenna heights. It also includes the possibility of the transmitter antenna height being less than or equal to the receiver antenna height.

$$\begin{aligned} L_{outside} &= [51 - 8\log(H_{TX}H_{RX})]\log(d) + 8.4\log(H_{TX}H_{RX}) \\ &+ 20\log(f_c/2.2) + 14 \end{aligned} \tag{3.14}$$

where d is the distance between transmitter and receiver, H_{TX} is the transmitter's antenna height, H_{RX} is the antenna height in the receiver; f_c is the frequency. This model is used to obtain $L_{(BS\text{-}CPE)}$ and $L_{(CPE\text{-}BS)}$ in (3.4) and (3.5), respectively.

3.4.2.3 *Indoor Propagation Model*

To model the propagation losses between a transmitter and a receiver located inside the same building, we used the model described in [95], as expressed by:

$$L_{indoor} = L_0 + L_C + \sum_{i=1}^{I} k_{wi} L_{wi} + k_f^{\left[\frac{k_f+2}{k_f+1} - b\right]} L_f \qquad (3.15)$$

where L_O is the free space loss, L_C is the constant loss, L_{wi} is the loss of wall type i, L_f is the loss between adjacent floors, k_{wi} is the number of penetrated wall of type i, k_f is the number of penetration floors (1...4), b is the empirical parameter fixed at 0.46. This model is used to compute the propagation loss L_p of the interferences defined in (3.6), (3.7), (3.8) and (3.9). It is worth noting that the application of this model is done considering that the transmitters and the receivers are in the same building.

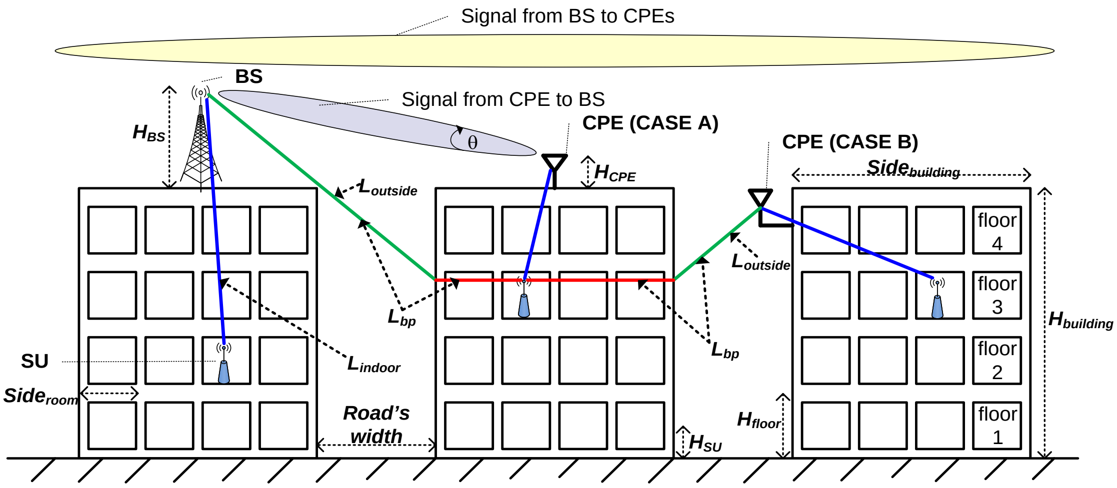


Figure 3.3 : Location of the Systems, and Use of the Propagation Models

3.5 Simulation Results

In this section, the reusable area is evaluated for Cases A and B identified in section 3.3.2. In both cases, a Manhattan layout of 500x500m^2 is considered with a total of 25 buildings uniformly distributed, as shown in Figure 3.4, in which T is a point in the scenario used to calculate the BS transmission power.

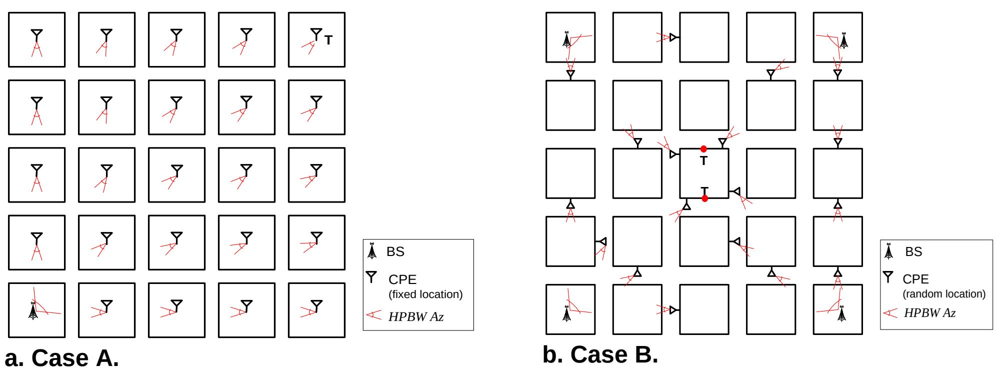


Figure 3.4 : Urban Scenario Represented by a Manhattan Model

The buildings have 4 floors with a height of 2.5m each. Each floor is $100x100m^2$ and has an internal distribution based on 5x5m compartments or rooms. Road's width is 20m. Scenario settings used in simulations are shown in Table 3.1.

Table 3.1: Scenario Settings

Parameter	Value
Base Station heigth, H_{BS}	12m
CPE heigth, H_{CPE}	12m
Secundary user heigth, H_{SU}	1.5m/Floor
Floor heigth, H_{floor}	2.5m
Building heigth, $H_{building}$	10m
Room side, $Side_{room}$	5m
Building side, $Side_{building}$	100m
Number of floors, N_{floor}	4
Number of buildins, $N_{building}$	25
Road's width	20m

Configuration parameters are shown in Table 3.2 [42], [91], [97], [98]. The protection margin *M* is assumed to be the same for primary and secondary receivers and is fixed at 30dB. This margin is composed of a shadowing margin of M_{SH} = 16.4dB and the remaining 13.6dB are dedicated as the interference margin M_I.

Table 3.2: Configuration Parameters

	BS	CPE	SU
Transmitter Power, *P*	Obtained by (4.3)	Obtained by (4.4)	15dBm
Sensitivity, S	-80dBm	-80dBm	-65dBm
Protection margin, *M*	30dB	30dB	30dB
Antenna type	Directional	Directional	Omnidirec-tional
Operating frequency, *F*	2GHz	2GHz	2GHz
Antenna gain, *G*	4dBi	14dBi	2dBi
Front/back ratio	-30dB	-30dB	0dB
Antenna height	12m	12m	1.5m/floor
CASE A			
HPBW Az	120º	60º	360º
HPBW El	20º	10º	360º
CASE B			
HPBW Az	180º	60º	360º
HPBW El	20º	10º	360º

Note that the considered shadowing margin allows for an estimation of the interference levels I_i, i=1..4, stated in expressions (3.6), (3.7), (3.8) and (3.9), which is valid for 95% of the cases under a lognormal shadowing characterization with a standard deviation of 10dB.

An important parameter of the antenna pattern is the Half Power Beamwidth (HPBW). This corresponds to the angular separation in which the magnitude of the radiation pattern decreases by 50% (i.e. -3 dB) from the peak of the main beam, so that, $HPBW_{AZ}$ is for the azimuth and the $HPBW_{El}$ for the elevation. Values used by propagation models presented in section 3.4.2 are shown in Table 3.3 [95], [99].

Table 3.3: Propagation Models Parameters

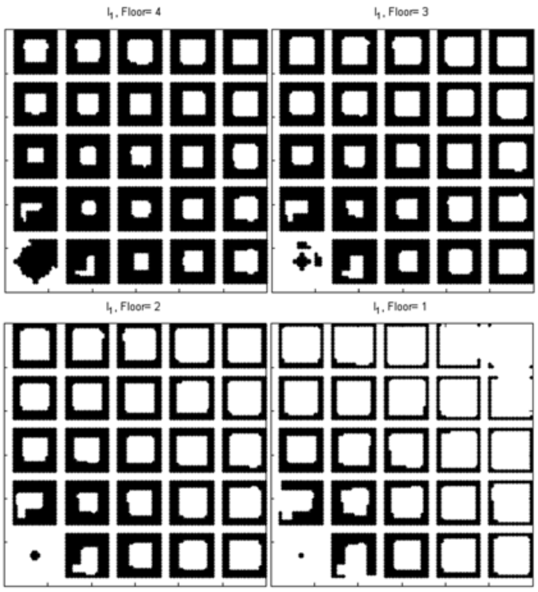
Parameter	Value
Building Penetration Losses	
Loss in the externally illuminated wall for $\phi = 90°$, W_e	7 dB
Additional loss in the external wall for $\phi = 0°$, W_{ge}	4 dB
Loss in the internal walls , W_i	6.9 dB
Number of internal walls , p	0,1,2,...
Loss per distance between adjacent walls , α	0.6 dB/m
Height gain, G_h	1.6 dB/m
Outside Propagation Model	
Frequency, fc	2 GHz
Indoor Propagation Model	
Constant loss , L_C	0
Loss of wall type i, L_{wi}	6.9 dB
Loss between adjacent floors, L_f	18.3 dB

3.5.1 Case A

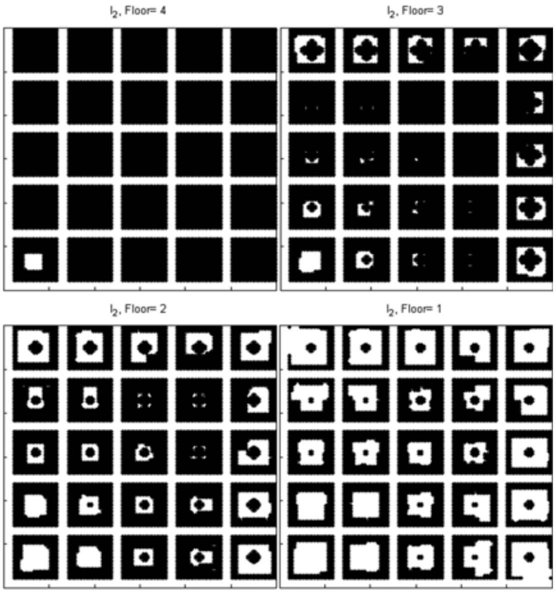
Initially, Case A is analyzed assuming that the BS is on the flat roof of a building located in one of the corners of the Manhattan layout, while the CPEs are distributed on the flat roofs of the other buildings. The transmission power of the BS is calculated using expression (3.4) and considering that coverage is provided to the roof of the farthest building with respect to the BS (e.g. point T shown in Figure 3.4a), so that the obtained BS transmission power is 45.22 dBm. Likewise, the transmission power of each CPE is calculated from (3.5) and depends on the location of each CPE within the considered scenario.

Figure 3.5 shows the accomplishment of each interference condition independently over each floor of the buildings. The white color in the figure represents the zones where each interference condition is fulfilled (e.g. C1: $I_1 <= S_{SU}-M_{SU}$). On the other hand, the black color refers to the cases where each interference condition is not satisfied.

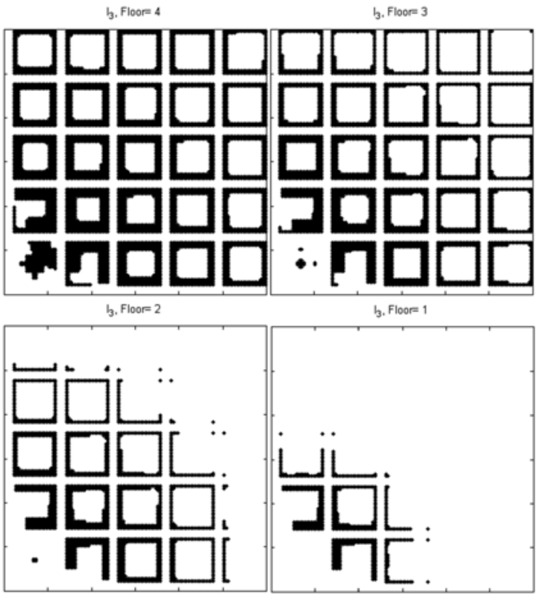
From the figure, the most restrictive interference condition is the one that considers the interference caused from the CPE transmitters to the SU receivers, C_2, as shown in Figure 3.5b. This is due to the density of CPEs in the study scenario (i.e. a CPEs over each building), as well as,the transmission power used by CPEs. Otherwise, interference condition C_4 is less restrictive than C_2, due to each SU transmitting signals of short range, see Figure 3.5d. However, the least restrictive interference condition is C_3. This is caused by the short coverage of SUs, as shown in Figure 3.5c. Note that, for all interference conditions, the reusable areas are greater on lower floors.



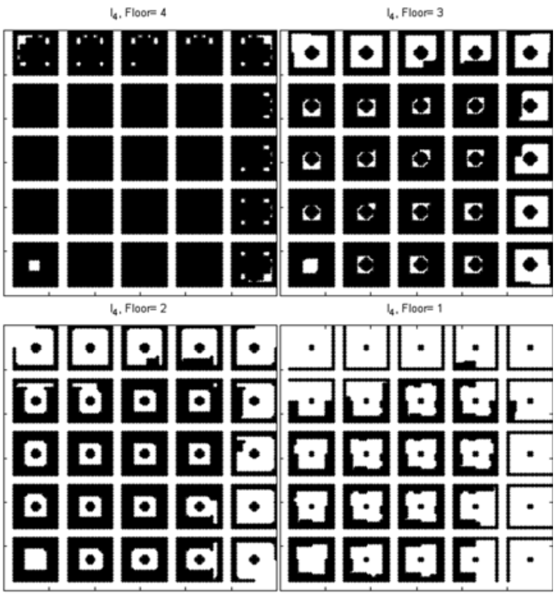
a. Interference Condition *C_1*



b. Interference Condition *C_2*



c. Interference Condition *C_3*



d. Interference Condition *C_4*

Figure 3.5 : Accomplishment of Each interference Condition per Floor, Case A

Figure 3.6 shows the spatial availability of the primary band on each floor of the buildings. The white color in the figure represents the superposition of the zones where interference conditions C_1 to C_4 are fulfilled. On the other hand, the black color refers to the cases where interference conditions are not satisfied. Recall that these conditions are necessary to consider that there is spectrum reusability.

As shown in Figure 3.6, spectrum availability is very limited on the 3rd and 4th floors due to the fact that: (a) higher floors are exposed to higher interference from the primary transmissions, and (b) the secondary transmissions are prone to generate interference on primary receivers that are located on the roof of the building. These issues, along with the directivity of primary antennas, cause interference concentrations on the highest floors.

On the other hand, the reusable area is available inside the buildings due to the following reasons: (a) transmissions of primary and secondary systems are highly attenuated by the walls and windows outside the buildings, so the interference inside of them decreases; (b) buildings located on the border of the layout do not receive interference from other CPEs in the outside part of the scenario; (c) in the buildings close to the BS because the CPEs on these buildings transmit with less power, causing less interference.

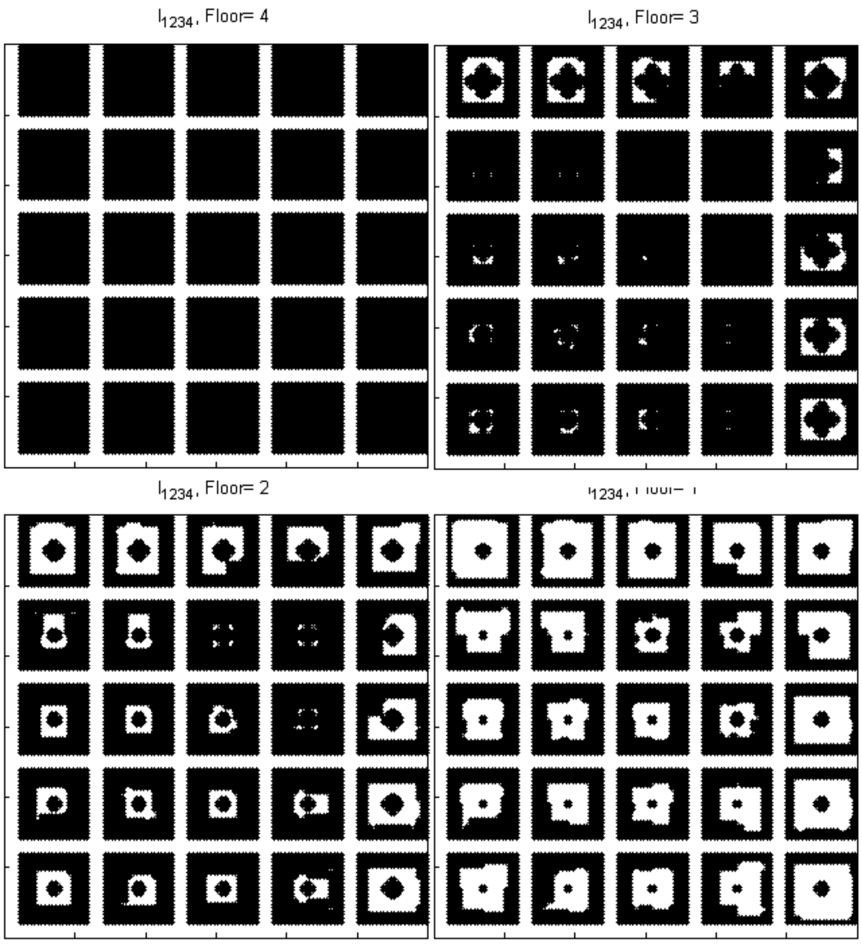


Figure 3.6: Spatial Availability of the Primary Band Inside the Buildings, Case A.

Table 3.4 presents the percentage of reusable area for each interference condition as well as the superposition of all these conditions on each floor of all of the buildings in the scenario. It is observed that C_2 is the most restrictive condition, so the average over all floors of the corresponding reusable area (i.e. RA_2) is around 18%. On the other hand, interference condition C_3 is the least restrictive interference which, in turn, leads to an average reusable area (i.e. RA_3) of 73.649% over all floors. Note that this table allows for the quantifying of the reusable zones shown in Figure 3.5 and Figure 3.6.

In this context, the overall reusable area is mainly affected by C_2, so the average reusable area (i.e. RA) is 17% over all floors. As shown in Table 3.4, as we move vertically inside the buildings away from the primary transmitters, the reusable area increases from 0% on the 4^{th} floor to 39.31% on the 1^{st} floor, given that the signals transmitted by the different systems have high propagation losses when they cross floors.

Table 3.4: Percentage of Reusable Area for Case A.

	$Floor_1$	$Floor_2$	$Floor_3$	$Floor_4$
RA_1	67.82	47.64	35.56	24.96
RA_2	41.44	22.06	9.51	0.63
RA_3	94.35	82.45	66.04	51.93
RA_4	61.33	39.44	22.13	2.71
RA	**39.31**	**20.01**	**7.46**	**0**

Then, some configuration parameters have been modified for analyzing the reusable areas, especially those related to C_2, because it was seen as the most restrictive interference condition.

Figure 3.7 shows how the reusable area is affected by the considered protection margin for secondary users (M_{SU}). It is observed that for M_{SU} values below 15dB, the resulting *RA* is constant because the interference received in the SU from the primary devices is lower than the term S_{SU}-M_{SU} in the conditions C_1 and C_2, while C_3 and C_4 do not change, so that secondary receptors are least sensitive to interferences. For M_{SU} values above 15dB, the sensitivity of the secondary receivers increases and the reusable area begins to decrease. For instance, if M_{SU} decreases from 50dB to 15dB, the reusable area on floor 1 increases approximately 55.29 percentage points. In conclusion, the reusable areas are very sensitive to changes in the SU protection margin.

Another parameter analyzed is the CPE azimuth angle ($HPBW\ Az_{CPE}$). By changing this angle on the horizontal plane from 90° to 15°, an average increase of reusable area of 11.61 percentage points is obtained over all floors, see Figure 3.8. For instance, an increase of 11.23 percentage points over the fourth floor is achieved by this angle variation. This is because the receivers receiving signals from CPEs are less exposed to these signals. Also, this leads to the antennas having a more meticulous installation and ongoing maintenance to maintain their direction.

Until now, Case A has been studied by considering 100% of CPEs on each flat roof of each building. Next, reusable areas are analyzed for different sets of CPEs on the scenario. For this simulation, a set of CPEs is uniformly distributed on the scenario for a certain number of snapshots (e.g. 20 for this study). Unlike the above results, a significant amount of reusable area on the top floor can be observed, mainly because a lower amount of CPEs reduces interference areas, I_2. For instance, decreasing CPEs from 100% to 8%, the RA increases around 21.53 percentage points on floor 4; also all floors have an average increase of reusable area of 9.21 percentage points as shown in Figure 3.9.

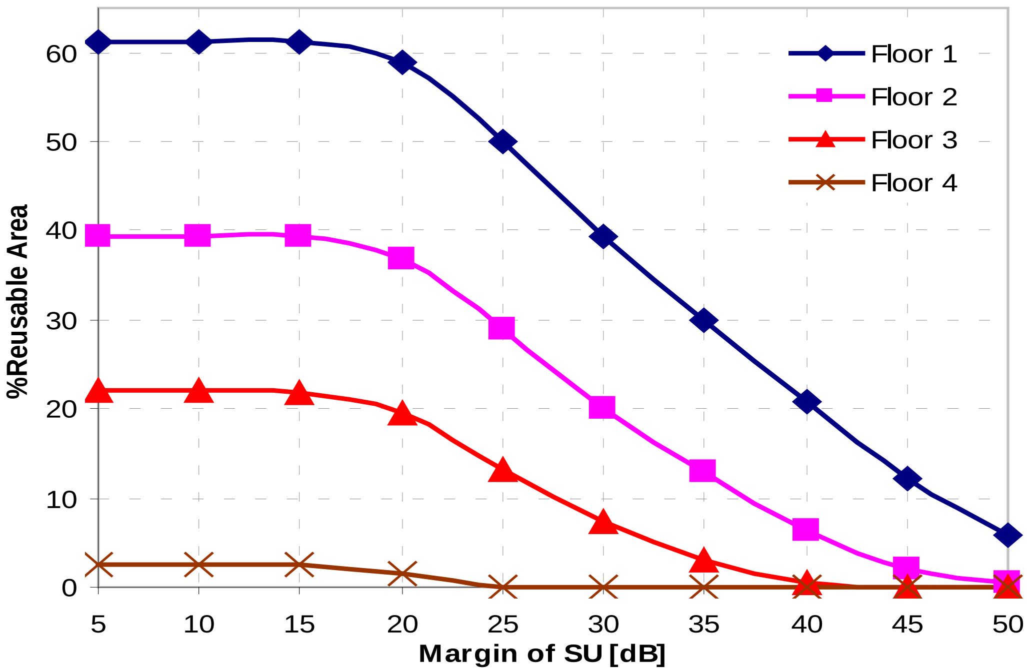


Figure 3.7: Percentage of Reusable Area versus Protection Margin of Secondary Users (MSU), Case *A*

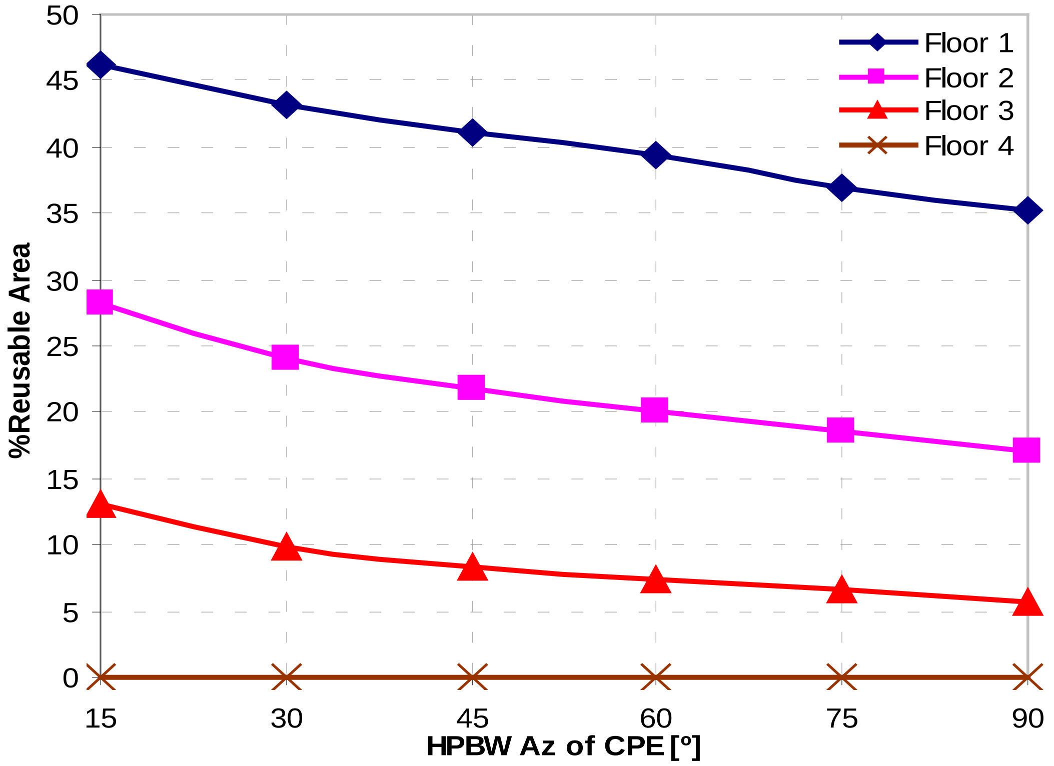


Figure 3.8: Percentage of Reusable Area versus HPBW Az (º)

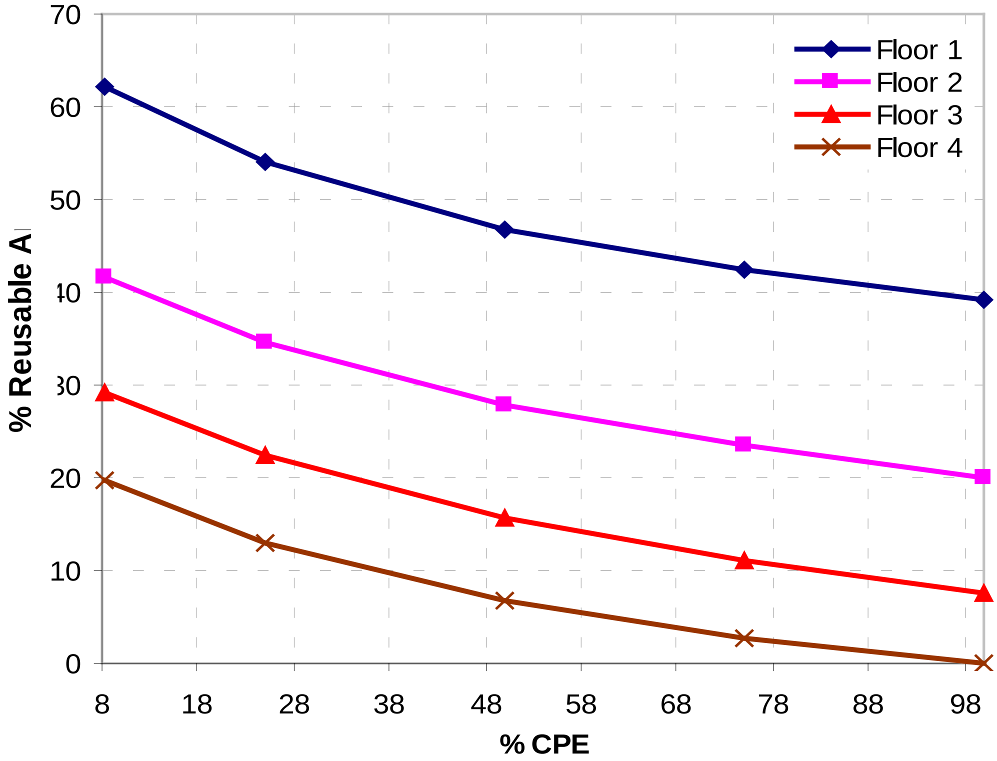


Figure 3.9: Percentage of Reusable Area versus %CPE.

3.5.2 Case B

In this case, four BSs on flat roofs of the buildings have been located in the corners of the scenario layout, while CPEs are assumed to be on external windows of the other buildings. Similar to the previous case, the transmission power of BSs is calculated by means of (3.4), resulting in a power value of 43.81dBm. We consider that the signal from each BS in the corner communicates with a CPE located in the lower external windows of the central building (see point T in the Figure 3.4b).

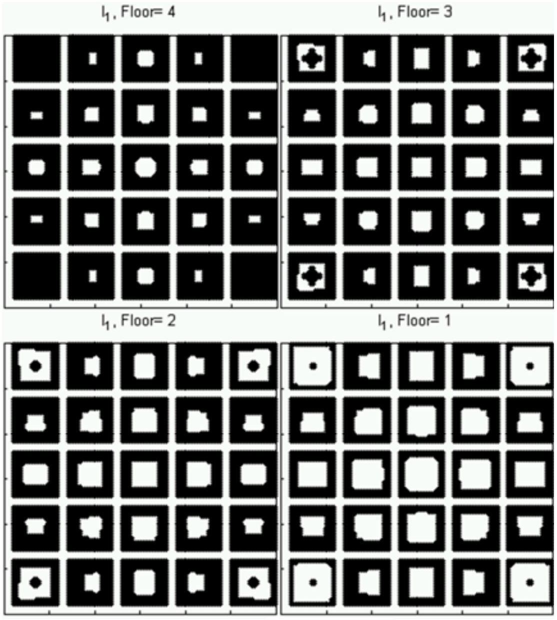
The transmission power of the CPE is calculated using expression (3.5), considering that each CPE is directed to the BS with better reception. Ninety-six CPEs are uniformly distributed in the scenario, resulting in an average of 24 CPEs per coverage zone of each BS using 20 snapshots for each CPE set. The HPBW Az of the BSs is increased from 120 to 180, given that the coverage on external windows from adjacent buildings is necessary.

Figure 3.10 shows a snapshot of the accomplishment of each interference condition per floor in the buildings. Areas where C_1 is fulfilled are differentiated from Case A due to the increase of BSs, thus this interference condition can be achieved in the center of the buildings and zones that are far from the BSs, as shown in Figure 3.10a. Since the CPEs do not have predetermined locations, as in Case A, the reusable areas for C_2 show irregular shapes, Figure 3.10b. Reusable areas for C_3 show a shape that depends on the position of BSs, Figure 3.10c. The obtained reusable area for C_4 has a similar shape to C_2 and depends on the location of the CPEs and SUs, Figure 3.10d.

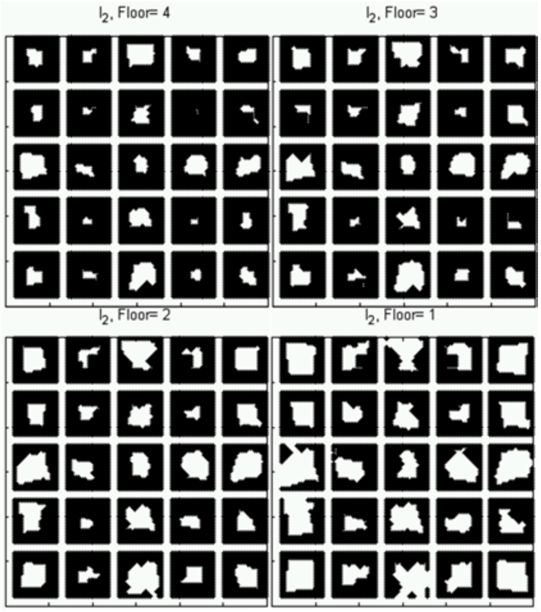
The percentages of reusable area for Case B are shown in Table 3.5. Similar to Case A, the average reusable area over all floors is more influenced by RA_2 than RA_3, with an average reusable area of 24.30% and 49.88%, respectively. The average of *RA* is 15.95%., which is similar to the one obtained in Case A. The difference is that, in Case B, the average value of *RA* is achieved over all floors. Figure 3.11 shows a snapshot of the superposition of the interference conditions.

3.6 Conclusions

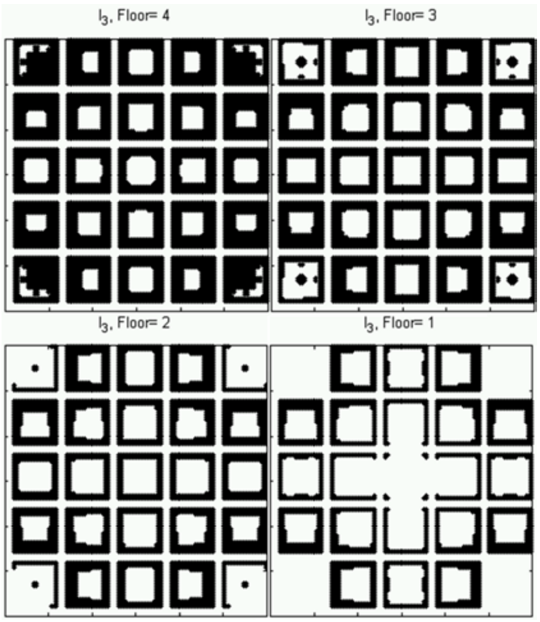
In this chapter, we have quantified the percentage of locations where it is possible to exploit OSA for secondary short-range radio communications systems within indoor locations in dense urban areas. The spectrum band to be reused is that of a primary system that provides outdoor coverage within the considered area. The analysis has been conducted assuming a typical building layout for dense urban areas and relying on well-known propagation models to characterize outdoor, outdoor to indoor and indoor propagation. In particular, four different conditions for spectrum reusability have been identified according to the different types of interferences arising in the scenario. Results demonstrate the amount and spatial distribution of the reusable area attending to different system configuration parameters.



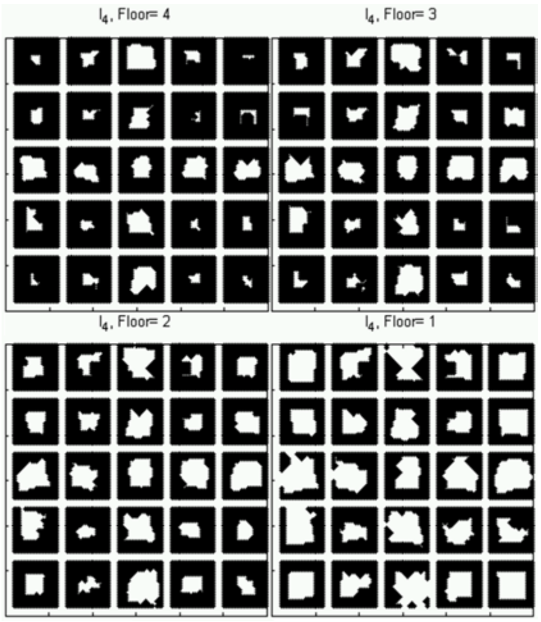
a. Interference Condition *C_1*



b. Interference Condition *C_2*



c. Interference Condition *C_3*



d. Interference Condition *C_4*

Figure 3.10: Effect Caused by Each Interference Condition Independently Inside the Buildings, Case B

Table 3.5: Percentage of Reusable Area for Case B

	$Floor_1$	**$Floor_2$**	**$Floor_3$**	**$Floor_4$**
RA_1	45.04	29.4	19.6	9.92
RA_2	37.63	26.15	18.94	14.5
RA_3	73.48	56.08	42.24	27.72
RA_4	41.99	27.76	19.73	15.08
RA	**28.89**	**17.86**	**10.38**	**6.69**

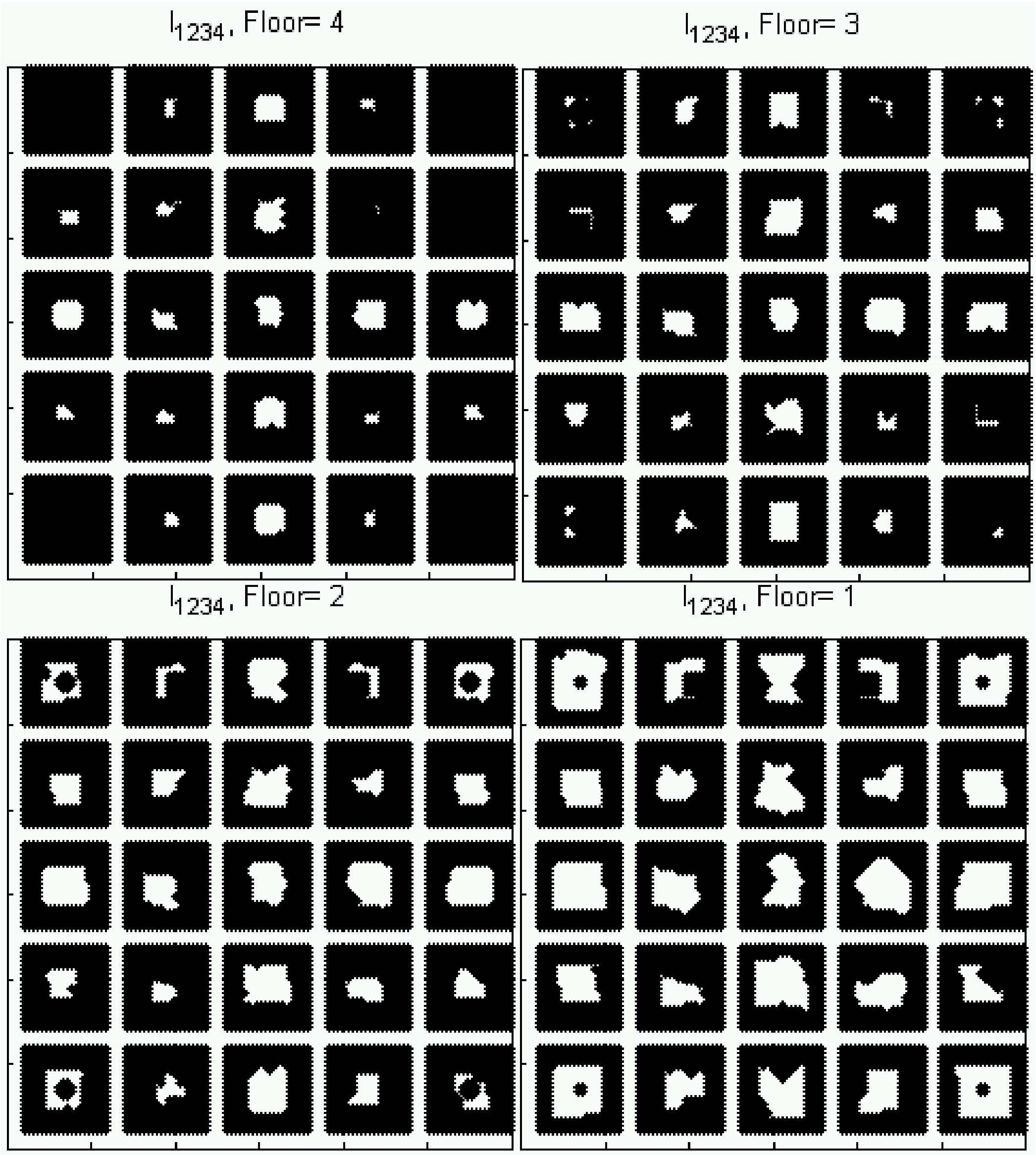


Figure 3.11: Spatial Availability of the Primary Band Inside the Buildings, Case B.

Chapter 4. **System Modeling of OSA-enabled WLAN Scenarios**

4.1 Introduction

In this chapter, a system model intended to describe and represent the main components involved in an OSA-enabled WLAN scenario is developed. The system model is the basis for the development and performance evaluation of the channel assignment algorithms presented in the next chapter.

The system model is schematized in Figure 4.1. This model allows a network scenario with primary and secondary systems to be configured. The deployment layout and the main power and spectrum usage parameters can be configured in a different way for each system. It also supports the planning of frequencies to be assigned to each primary device.

Based on the above, the proposed model establishes a set of coverage and interference areas by using propagation models and procedures that quantify the coupling between the channel used by the transmitter device and the tuned channel in the receiver device.

The first area type refers to zones where a transmitted signal can be received by the receiver devices of the same system, called usage areas in the following. Interference areas refer to zones where a transmitter device transmitting on a certain channel can be received by receiver devices tuned to the same or adjacent channels, called interference areas in the following. Hence, interference areas represent the spatial area in which a receiver would be exposed to an unacceptable level of interference generated by a transmitter.

Then, in order to define interference conditions for determining the available primary channels that can be used by WLANs devices, a new metric that allows the interference levels among users to be quantified is proposed. These interference conditions are based on the conditions of spectrum reuse established in Section 3.3.1.

Also, a constraint that is used for determining the channel assignment of WLANs is defined. This restriction can be calculated in terms of metrics based on the interference level, network capacity, etc.; however, as it was previously defined as an interference metric, this will also be used for this calculation.

Additionally, in this chapter, the opportunistic scenario is represented as a graph in order to represent the users' distribution on the scenario and the interference constraints among them. In this graph, the users are defined as vertices and the interference among them as edges.

The remainder of the chapter is organized as follows: In Section 4.2, parameters and features of the systems are established. The spectrum model used to represent the interference characterization among devices and propagation models are presented in Section 4.3. Usage and interference areas are defined in Section 4.4. The interference-based metric is defined in Section 4.5. Conditions for determining primary spectrum availability are established in 4.6. In Section 4.7, channel assignment constraint for WLANs is defined. The scenario is represented as a graph in Section 4.8. Case study is proposed and evaluated in Section 4.9. Finally, concluding remarks are discussed in Section 4.10.

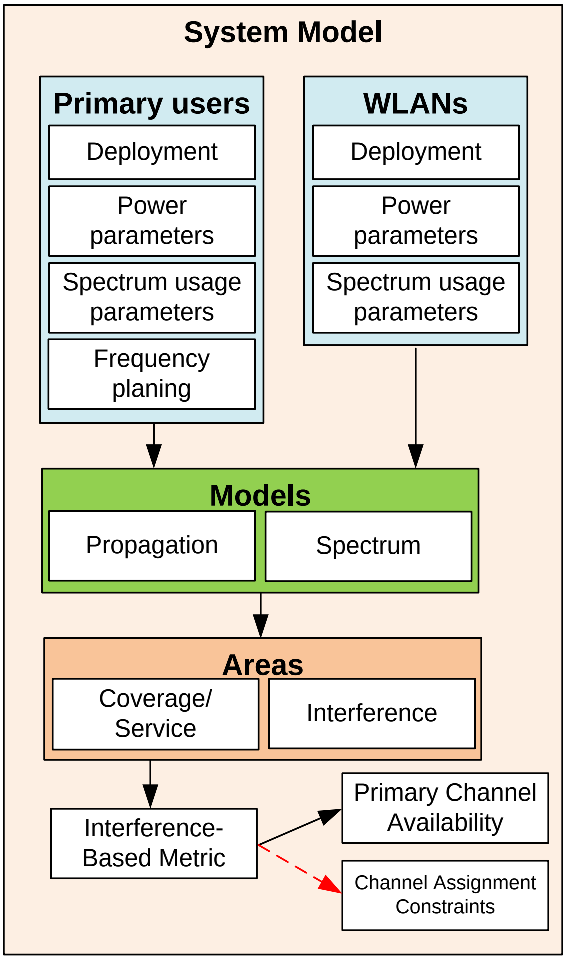


Figure 4.1: **System Model Scheme**

4.2 Components Description

Two systems formed by primary users and WLANs are each deployed on a network scenario as shown in Figure 4.2. It consists of a limited geographical area of *axb*, where users may incur interference to one another. Users could be deployed on the scenario by using any probabilistic distribution model; in particular, for this work, these are uniformly distributed on this area.

The power parameters refer to the energy levels that are allowed by the users. Among them, in this work, the transmission power, sensibility and the protection margin are considered.

In relation to the spectrum usage parameters, the operating channel used by each AP would either be a channel belonging to the ISM band, as supported by legacy WLANs, or a channel located in another frequency band properly regulated to allow OSA (e.g. TV bands). This additional band is referred to as the primary band (PB) where WLAN operation is allowed whenever the primary service using this band is not disturbed.

Considering OSA notation, the WLAN devices are referred to as secondary users (SUs) of the licensed (primary) band owned by the primary system, whose correspondent devices are named as primary users (PUs). The availability of the PB channels for opportunistic utilization in each AP depends on the presence and frequency assignment of the PUs.

The set of available channels for WLAN operation is considered to be $\mathbb{C}_{ISM}$ and $\mathbb{C}_{PB}$ in the ISM and PB bands, respectively. Thus, the number of potential channels to be used in any WLAN network ranges from C_{ISM} to $C_{ISM} + C_{PB}$. Channelization, transmission mask characteristics, and transmission/reception parameters for WLAN operation in both bands is considered to be as defined in current 802.11 specifications, as described in Chapter 2.

Spectrum usage parameters for primary users are considered to be different from those used by WLANs. In particular, channelization and transmission mask characteristics are similar to those used by TV band. Hence, the channel used by WLAN in primary band corresponds to a set of adjacent primary channels such as those used by primary users. These parameters will be set in section 4.10. The frequency planning for primary users is realized so that the primary channels are uniformly assigned to each primary user. For WLANs, this will be determined by the channel assignment mechanisms developed in the next chapter.

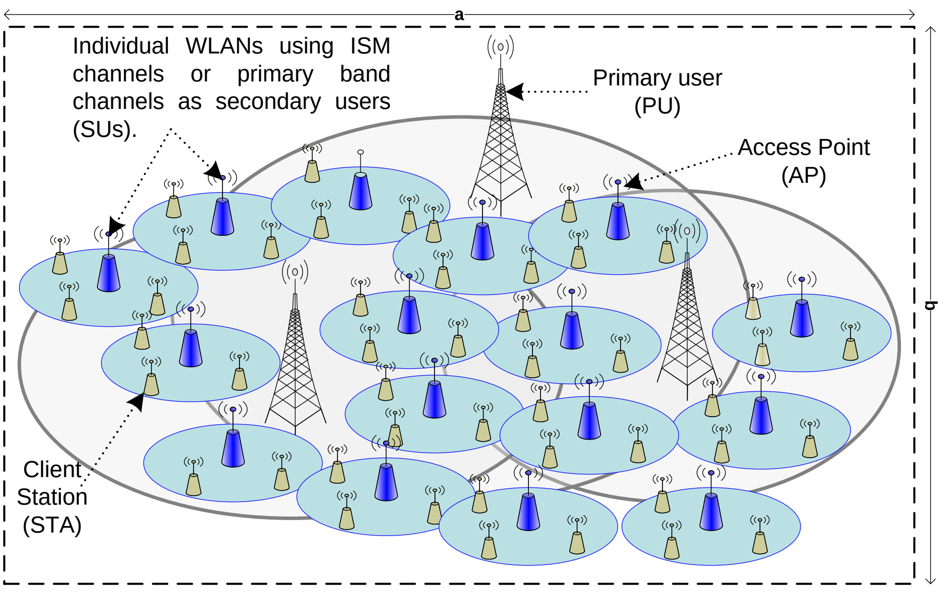


Figure 4.2: Network Scenario

4.3 Spectrum and Propagation Models

Spectrum Model

Interference characterization between primary users and WLAN devices, as well as between neighboring WLAN networks, is modeled by considering the spectral factor developed in [100]. This depends on the spectral characteristics of the interfering transmitter and the frequency response of the victim receiver.

This factor allows the amount of interference caused by a transmission centered at frequency f_i into a receiver tuned at frequency f_j to be quantified. The amount of overlapping is captured quantitatively by calculating the area of intersection between the interfering signal's power spectral density (PSD) (denoted as $P_I(f)$ and the receiver's band-pass filter frequency response (denoted as $H_R(f)$), as shown in Figure 4.3.

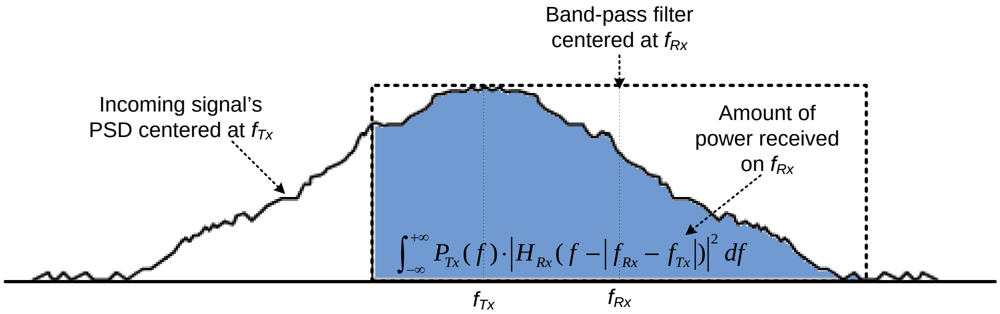


Figure 4.3: Transmission Power and Band-Pass Filter Masks at the Receiver

On such a basis, the normalized received power at the output of the receiver filter is referred to as overlapping interference factor, ρ, and can be calculated by means of the following expression:

$$\rho_{I^i \to R^j} = \frac{\int_{-\infty}^{+\infty} P_I(f)\cdot\left|H_R\left(f-\left|f_j-f_i\right|\right)\right|^2 df}{\int_{-\infty}^{+\infty} P_I(f)df} \tag{4.1}$$

where i and j correspond to the number indexes of the frequency channels used by the interference (I) and the receiver (R) devices, respectively. This factor can be derived for any band-limited signal regardless of its modulation method and can also be used between devices of the same or different wireless technologies.

Hence, according to the network scenario considered in this work, the interference characterization relies on the calculation of three different overlapping interference factors:

1) $\rho_{SU^i \to PU^j}$,obtained when an interfering signal from an SU transmitter (WLAN device) using a channel is present at the PU receiver:

$$\rho_{SU^i \to PU^j} = \frac{\int_{-\infty}^{+\infty} P_{SU}(f) \cdot \left| H_{PU}(f - |f_j - f_i|) \right|^2 df}{\int_{-\infty}^{+\infty} P_{SU}(f) df} \quad (4.2)$$

2) $\rho_{PU^i \to SU^j}$,in the case that the SU receiver is exposed to an interfering signal from a PU transmitter:

$$\rho_{PU^i \to SU^j} = \frac{\int_{-\infty}^{+\infty} P_{PU}(f) \cdot \left| H_{SU}(f - |f_j - f_i|) \right|^2 df}{\int_{-\infty}^{+\infty} P_{PU}(f) df} \quad (4.3)$$

3) $\rho_{SU^i \to SU^j}$, to characterize the interference between two WLAN devices operating on partially-overlapping channels either in the ISM or PB band:

$$\rho_{SU^i \to SU^j} = \frac{\int_{-\infty}^{+\infty} P_{SU^i}(f) \cdot \left| H_{SU^j}(f - |f_j - f_i|) \right|^2 df}{\int_{-\infty}^{+\infty} P_{SU^i}(f) df} \quad (4.4)$$

Propagation Model

The propagation model used to characterize the propagation loss of a signal transmitted by a certain device and received by another is defined as follows:

$$L = L_o + 10 \cdot \alpha \cdot \log R \quad (4.5)$$

where L_o is the channel attenuation at 1m, α is the propagation slope, and R corresponds to the distance between the transmitter and receiver devices.

4.4 Usage Areas

Considering that, the radio signals transmitted by PUs and WLANs are emitted through omnidirectional antennas and the coverage/usage area is represented by means of circular shapes.

The power received at the limit of coverage area by any receiver of a certain system y is given by:

$$P_{Rx,y} = P_{Tx,y} - L_o - 10 \cdot \alpha \cdot \log R_{UA,y} = S_y \quad (4.6)$$

where $P_{Tx,y}$, $R_{U,y}$, S_y are the transmitted power, radius of usage area, and sensibility of the system y, respectively. Hence, y is either PU or SU.

Thus, the radius of usage area of secondary (UA_{SU}) or primary (UA_{PU}) users can be calculated by means of the following equation:

$$R_{UA,y} = 10^{\frac{(P_{Tx,y} - S_y) - L_o}{10\alpha}} \quad (4.7)$$

For instance Figure 4.4 shows, the coverage area from a certain *ap* to its linked STA.

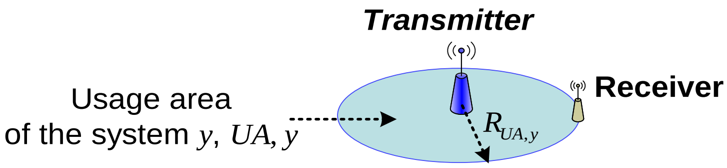


Figure 4.4: Usage Radius

4.5 Interference Areas

The zones where a transmitter device transmitting on a certain channel can be received by receiver devices tuned in to the same or adjacent channels are referred to as interference areas. Similar to the way in which the usage areas were defined, the interference areas are also represented by circular shapes and are described below.

4.5.1 Interference Areas from PU to SU

The radio of the interference area caused by a certain primary transmitter to secondary receivers ($IA_{PU \to SU}$) is obtained by considering a scenario, as shown in Figure 4.5. Note that in this scenario only the base station (BS) PU can transmit in all of the usage area.

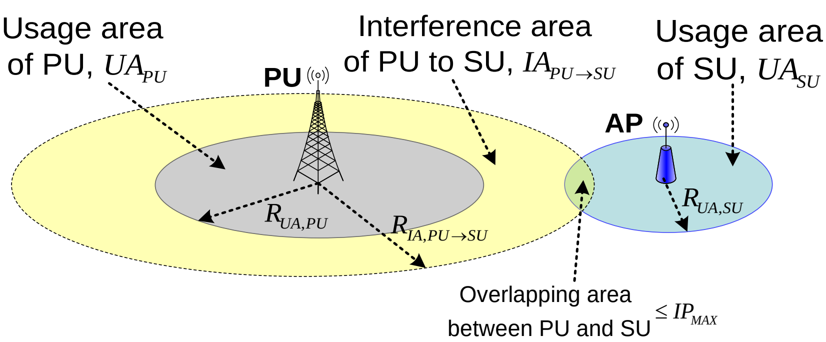


Figure 4.5: Interference Condition from PU to SU

The radio of the interference area of PU to SU is computed as follows:

The transmission power of a PU is computed by using (4.6):

$$P_{Tx,PU} = S_{PU} + L_o + 10 \cdot \alpha \cdot \log(R_{UA,PU}) \qquad (4.8)$$

By using the same equation, the power received at an SU from a PU (i.e. $I_{PU \to SU}$) is given by:

$$P_{Rx,SU} = P_{Tx,PU} - L_o - 10 \cdot \alpha \cdot \log(R_{IA,PU \to SU}) - \Delta_{PU^i \to SU^j} \qquad (4.9)$$

where $\Delta_{PU^i \to SU^j}$ is the interference factor in dB, so that, $\Delta_{PU^i \to SU^j} = -10 \log \rho_{PU^i \to SU^j}$, $\forall\ \rho_{PU^i \to SU^j} > 0$.

Notice that, for (4.6) the interference factor is not considered because the transmitter and the receiver are considered to be tuned to the same channel; however for (4.9), the receiver could be tuned to a different channel than the transmitter, so it is necessary to consider this factor.

Next, (4.8) and the interference condition defined in (3.2) are equaled:

$$P_{Rx,SU} = I_{PU \to SU} \tag{4.10}$$

$$P_{Tx,PU} - L_o - 10 \cdot \alpha \cdot \log(R_{IA,PU \to SU}) - \Delta_{PU^i \to SU^j} = S_{SU} - M_{SU} \tag{4.11}$$

By replacing (4.8) in (4.11):

$$S_{PU} + \not{L_o} + 10 \cdot \alpha \cdot \log(R_{UA,PU}) - \not{L_o} - 10 \cdot \alpha \cdot \log(R_{IA,PU \to SU}) - \Delta_{PU^i \to SU^j} = S_{SU} - M_{SU} \tag{4.12}$$

Consequently, the interference radio from PU to SU is denoted as:

$$R_{IA,PU \to SU} = R_{UA,PU} \cdot 10^{\left(\frac{S_{PU} - S_{SU} + M_{SU} - \Delta_{PU^i \to SU^j}}{10 \cdot \alpha}\right)}, \quad \forall \ \rho_{PU^i \to SU^j}) > 0 \tag{4.13}$$

4.5.2 Interference Areas from SU to PU

The radio of the interference area caused by a certain secondary transmitter to primary receivers (i.e. $IA_{SU \to PU}$) is obtained by considering a scenario as shown in Figure 4.6. In this scenario, AP and its linked STA can transmit. Thus, any STA located at the limit of UASU can cause interference to PUs.

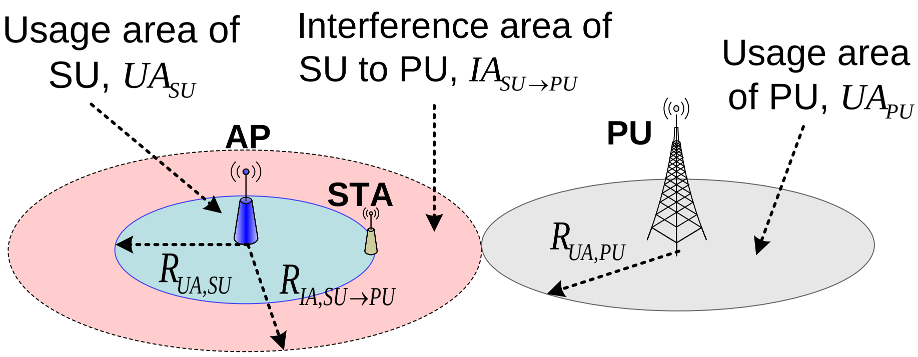


Figure 4.6: Interference Condition from SU to PU

The radio of the interference area of SU to PU is computed as follows:

The power received at a PU from an STA located at the limit of the UASU (i.e. $I_{SU \to PU}$) is given by using (4.6):

$$P_{Rx,PU} = P_{Tx,SU} - L_o - 10 \cdot \alpha \cdot \log(R_{IA,SU \to PU} - R_{UA,SU}) - \Delta_{SU^i \to PU^j} \tag{4.14}$$

Note that transmission and reception parameters are considered to be the same for AP and STA (e.g. $P_{Tx,AP} = P_{Tx,STA} = P_{Tx,SU}$).

Hence, from (4.6), the transmission power of SU into the usage area is computed as follows:

$$P_{Tx,SU} = S_{SU} + L_o + 10 \cdot \alpha \cdot (R_{UA,SU}) \tag{4.15}$$

Thus, (4.13) and the interference condition defined in (3.1) are equaled:

$$P_{Rx,PU} = I_{SU \to PU} \tag{4.16}$$

$$P_{Tx,SU} - L_o - 10 \cdot \alpha \cdot (R_{IA,SU \to PU} - R_{UA,SU}) - \Delta_{SU^i \to PU^j} = S_{PU} - M_{PU} \tag{4.17}$$

By replacing (4.15) in (4.17):

$$S_{SU} + \cancel{L_o} + 10 \cdot \alpha \cdot (R_{UA,SU}) - \cancel{L_o} - 10 \cdot \alpha \cdot (R_{IA,SU \to PU} - R_{UA,SU}) - \Delta_{SU^i \to PU^j} = S_{PU} - M_{PU} \tag{4.18}$$

Consequently, the interference radio from SU to PU is denoted as:

$$R_{IA,SU \to PU} = R_{UA,SU} \cdot \left(1 + 10^{\left(\frac{S_{SU} - S_{PU} + M_{PU} - \Delta_{SU^i \to PU^j}}{10 \cdot \alpha} \right)} \right), \quad \forall \ \rho_{SU^i \to PU^j} > 0 \tag{4.19}$$

As it is appreciated in (4.13) and (4.19), the interference radii are dependent on the overlapping factor. This is caused by overlapping between channels. Therefore, the maximum interference radio is caused when the transmitter and the receiver are tuned to the same channel.

4.6 Penalty

The penalty (*P*) is a metric that allows WLANs to quantify the interference levels between a pair of APs when they are using a certain pair of channels either from ISM band or primary band, see Figure 4.7.

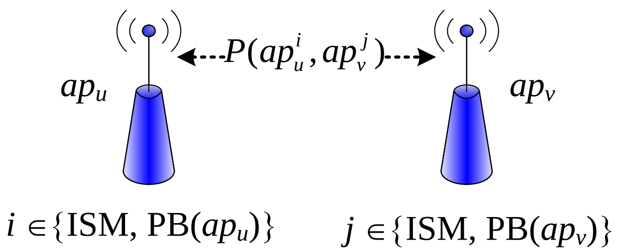


Figure 4.7: Penalty Factor Between APs

Building upon the concepts of usage and interference areas, the penalty is defined as the percentage of the usage area in which the correspondent availability condition will not be met. The *P* factor is computed as:

$$P(y^i, z^j) = \frac{\left[UA_z \cap IA_{y \to z}\left(\rho_{y^i \to z^j} \right) \right]}{UA_z} \tag{4.20}$$

in which *y* and *z* represent the interfering and interfered devices respectively, which can either be PU or SU. *UA* is the usage area of *z* and *IA* is the interference area between *y* and *z*. *i*, *j* correspond to the transmitter and the receiver channels, respectively. $\rho_{y^i \to z^j}$ is the overlapping interference factor, which corresponds to the normalized received power at the output of the receiver filter defined in the model of partially-overlapping wireless channels described in Section 4.3.1.

4.7 Primary Band Availability Conditions

Availability of primary channels to SUs (i.e. APs) is modeled according to the locations and the potential interference between PUs and SUs. In particular, conditions for determining which primary channels can be used by SUs are formulated in terms of the maximum interference levels that can be tolerated by both the PU and SU receivers. These conditions were defined in Section 3.3.1 as "Conditions of Spectrum Reuse" by means of the expressions (3.1) and (3.2).

Relying on the penalty definition, the possibility for an SU to use a given primary channel is determined according to the accomplishment of the following two conditions:

a) The amount of overlapping between the usage area of the SU and the interference area of a PU must not exceed a certain threshold (P_{MAX}), if $P_{MAX} > 0$. Thus, the condition is referred to as:

$$P(PU^i, SU^j) = \frac{\left[UA_{SU} \cap IA_{PU \to SU} \left(\rho_{PU^i \to SU^j} \right) \right]}{UA_{SU}} \leq P_{MAX} \tag{4.21}$$

where, IP_{MAX} is the maximum percentage of the SU usage area where a PU can cause interference (i.e. condition (3.2) could not be satisfied).

This means that the SU is allowed to operate, even under the presence of some amount of interference coming from PUs. The reason not to force $P(PU^i,SU^j)$ to zero in this case is because WLAN networks are considered to be able to successfully operate under a certain amount of co-channel or adjacent channel interferences [7]. The fulfillment of this condition is illustrated in Figure 4.5.

b) The usage area of a PU must not overlap with the interference area of an SU, this condition is determined by:

$$P(SU^i, PU^j) = \frac{\left[UA_{PU} \cap IA_{SU \to PU} \left(\rho_{SU^i \to PU^j} \right) \right]}{UA_{PU}} = 0 \tag{4.22}$$

Thus, since PUs have priority use on the primary band, the SUs are not allowed to use primary channels within the coverage range of the PUs. Therefore, condition (3.1) is going to be satisfied within the whole usage area of the PU. The accomplishment of this condition is illustrated in Figure 4.6.

4.8 Channel Assignment Constraint

Since, in previous sections, a metric based on interference levels has been defined, for the sake of simplicity, the channel assignment constraint for the individual WLAN networks is established by means of the penalty. In particular, a given pair of APs (ap_u and ap_v) is allowed to use a given pair of channels (i and j) when the following condition is satisfied:

$$P(ap_u^i, ap_v^j) = \frac{\left[UA_{ap_v} \cap IA_{ap_u \to ap_v}\left(\rho_{ap_u^i \to ap_v^j}\right)\right]}{UA_{ap_v}} \leq P_{MAX} \qquad (4.23)$$

being, UA_{ap_v} the usage area of AP v, and $IA_{ap_u \to ap_v}$ the interference area of AP u to AP v. The same condition applies regardless of whether the channels being considered are ISM or PB channels, as shown in Figure 4.8.

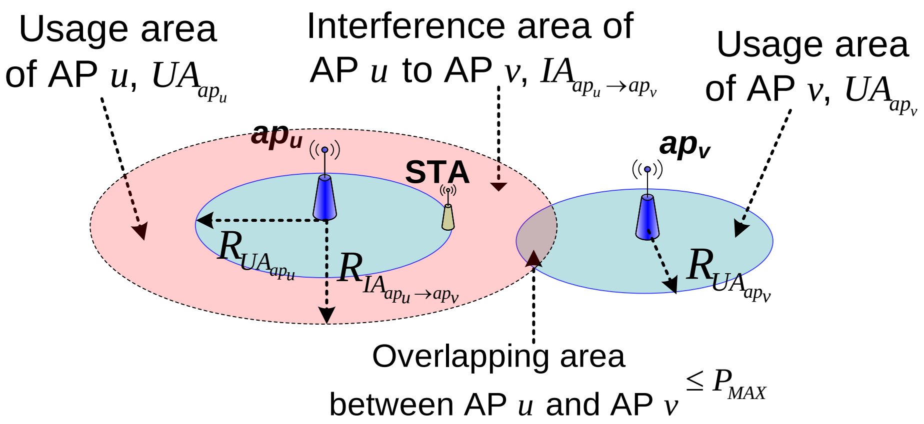


Figure 4.8: Interference Constraints Between APs

The interference radio of $IA_{ap_u \to ap_v}$ is determined in the same manner as (4.19) and is computed as:

$$R_{IA,ap_u \to ap_v} = R_{UA,ap_u}\left(1 + 10^{\left(\frac{M_{SU} - \Delta_{ap_u^i \to ap_v^j}}{10 \cdot \alpha}\right)}\right), \quad \forall \rho_{ap_u^i \to ap_v^j} > 0 \qquad (4.24)$$

Notice that the channel assignment constraint has been defined in terms of the penalty, which in turn depends on the interference between devices. However, this constraint could also be defined in terms of other network parameters such as throughput, signal power received and receiver CIR, among others.

4.9 Graph Representation

The WLAN network deployment on the network scenario is represented as a graph $G=(V,E)$, in which the vertices $V = \{ap_1, ap_2, ..., ap_N\}$ correspond to the N APs, and the edges

$E = \{ e_{u,v} = (ap_u, ap_v) \mid e_{u,v} \in \{0,1\} \}$ account for the interference conditions between the APs, as shown Figure 4.9.

In particular, an edge between two APs exists if the P factor calculated under co-channel conditions is greater than zero, as is described the following expression:

$$e_{u,v} = \begin{cases} 1, & P(ap_u^i, ap_v^i) > 0 \\ 0, & \text{otherwise} \end{cases} \tag{4.25}$$

The APs linked by an edge are defined as neighbors. Thus, for instance, the set of neighbors for ap_u is defined as: $B(ap_u) = \{ ap_v \mid \forall ap_v \in V, e_{u,v} = 1 \}$.

The color or channel eventually assigned to AP u is represented by $Ch(ap_u)$.

In the rest of this work, APs and vertices and, similarly, colors and channels will be used interchangeably.

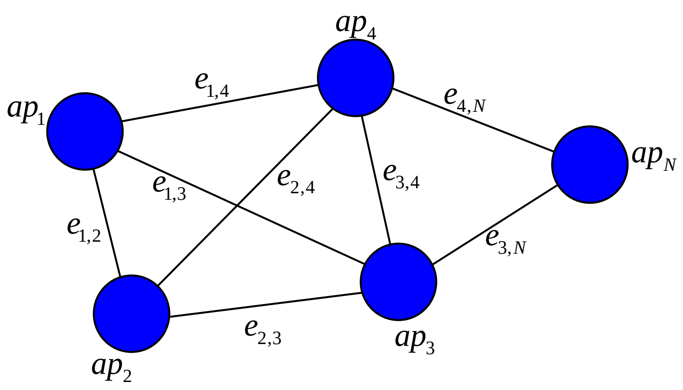


Figure 4.9: Scenario Represented as a Graph

4.10 Case Study

In this section a case study is proposed in order to analyze the performance of the proposed system model. This analysis considers the deployment of users on the scenario, usage and interference areas, penalties among users, and available primary channels.

To that end, a number of topology snapshots are generated by randomly placing primary and secondary users on an area of 1km×1km. In this particular study, for the sake of simplicity, the spectrum masks for primary and WLAN transmissions are considered to have a rectangular shape. Each PU is assumed to operate on a given channel of the primary band (randomly selected in this work). The primary band is set to have 10 non-overlapping channels with a bandwidth of 5 MHz each.

Hence, depending on the location of primary users and APs, and on the channels used by the primary users, the APs can have between 0 and 10 additional available channels in the primary band, in addition to C_{ISM}=11 channels in the ISM band.

Notice that, just as in ISM channels, contiguous PB channels are partially-overlapping channels when used for WLAN transmissions since WLAN signals are assumed to be spread over 22MHz. Simulation parameters used in these simulations are shown in Table 4.1.

The provided results were obtained from 5000 snapshots and evaluated by using MATLAB. A computer with processor Intel Core 2 Quad of 2.4GHz and 5.9GB of RAM has been used for these simulations.

Table 4.1: Simulation Parameters

Parameters	Value
Protection margin of SU, M_{SU}	10dB
Protection margin of PU, M_{PU}	15dB
Sensitivity of SU, S_{SU}	-65dBm
Sensitivity of PU, S_{PU}	-65dBm
Propagation slope, α	3.5
Maximum Penalty, P_{MAX}	0.2
Number of primary channels, C_{PB}	10
Number of primary channels, C_{ISM}	11
Primary channel bandwidth	5MHz
WLAN channel bandwidth	22MHz

4.10.1 Deployment of users and areas

A snapshot of the network scenario is illustrated in Figure 4.10, which shows the usage and interference areas of the AP and primary users. Radio operation parameters of the two systems have been chosen to have the following usage and interference area radii: $R_{UA,SU}$=50m, $R_{UA,PU}$=100m, $R_{IA,PU\rightarrow SU}$= 193m, $R_{IA,SU\rightarrow PU}$= 184.1m, $R_{IA,ap_u\rightarrow ap_v} = 75.8\text{m}$. Note that the interference radii correspond to the maximum interference that each device can cause to another. This is the case when devices use the same channel.

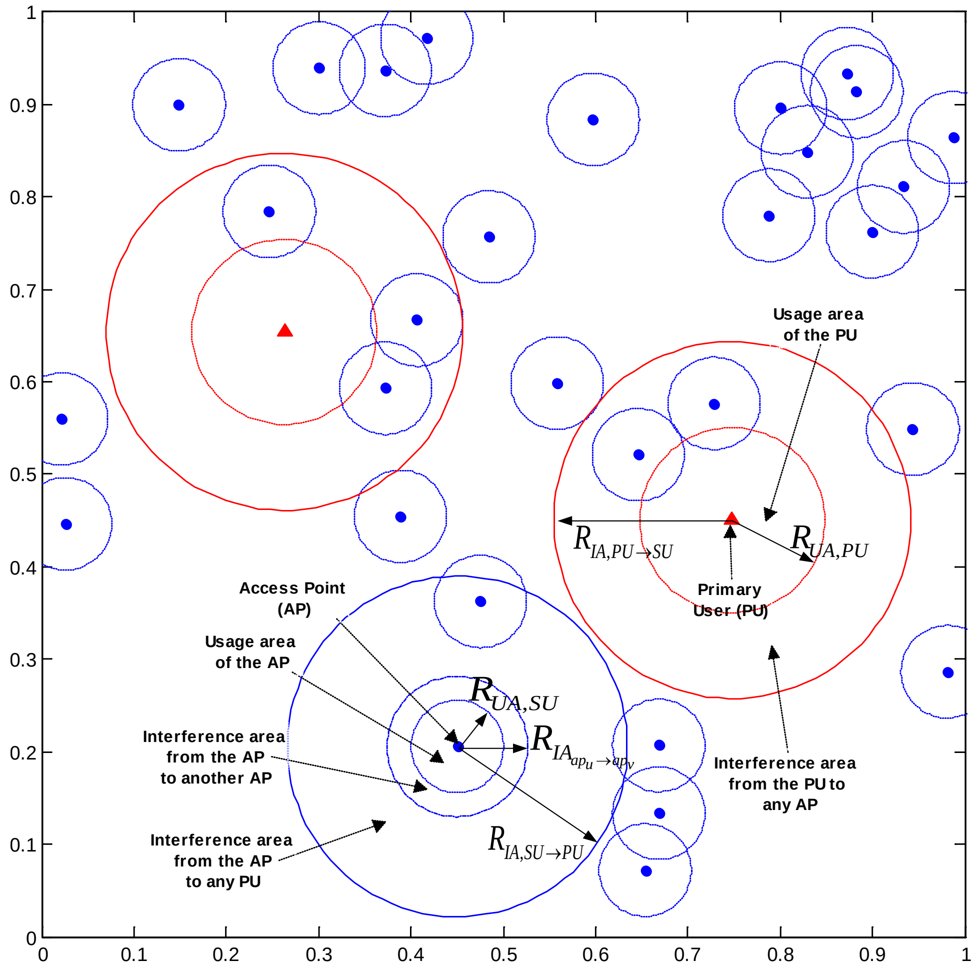
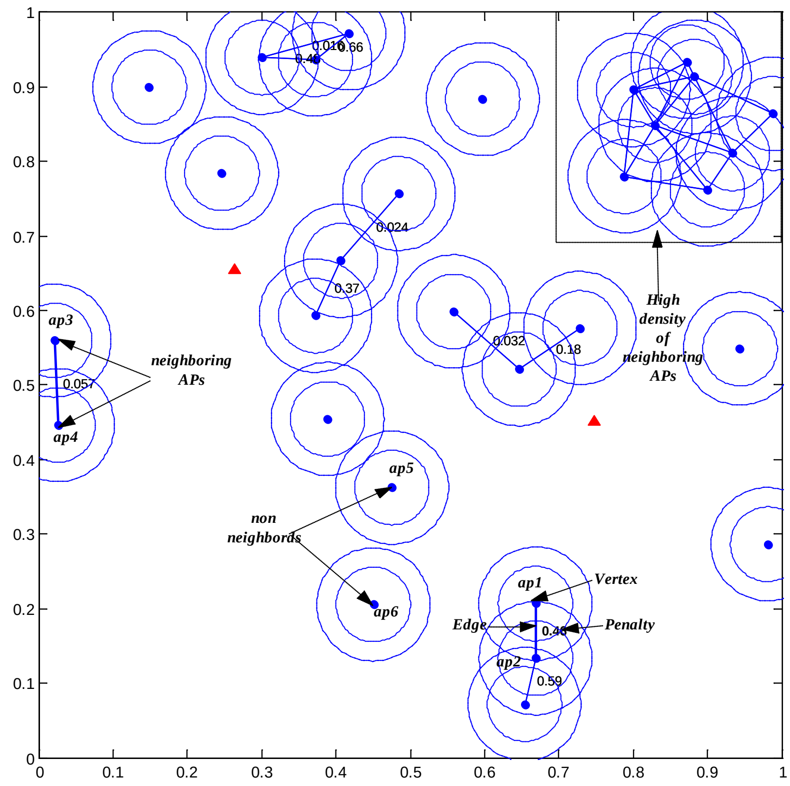


Figure 4.10: Snapshot of the Simulation Scenario

4.10.2 Penalties among users

Figure 4.11a shows the scenario represented as a graph, where usage and interference areas are illustrated for each AP and the edges between APs along with the corresponding penalty for co-channel conditions (see ap_1 and ap_2). For instance in Figure 4.11a, ap_3 and ap4 are considered as neighbors since their penalty is greater than cero in particular $P(ap_3, ap_4)$=0.057, which corresponds to overlapping area among interference and usage areas of both APs. However, for ap_5 and ap_6 the overlapping area does not exist, therefore, these access points are not considered to be neighbors.

A zoom of the high density of neighboring APs zone is shown in Figure 4.11b. This figure depicts that the penalty between ap_7 and ap_8 is equal to one; due to, that the usage area of ap_7 being completely within the interference area of ap_8. Also, it is observed that ap_9 is the AP with the largest amount of neighbors (e.g. six neighbors).



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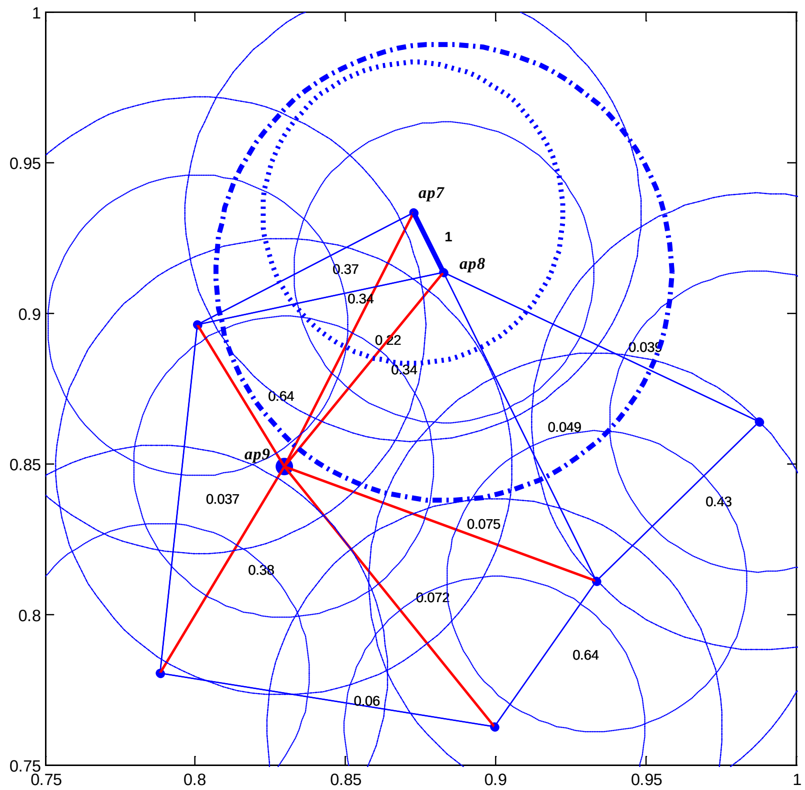


b.

Figure 4.11: Scenario Represented as a Graph

Density of APs deployed in the scenario can be analyzed by the amount of neighboring APs. Because of this, Figure 4.12 shows the Cumulative Distribution Function (CDF) for the amount of neighbors per AP for different sets of APs in the scenario. From this figure, it is possible to appreciate that, for a high density of APs in the scenario, the probability that an AP has more neighbors is higher than for low densities. So, for instance, for 50 APs in the scenario, the probability that an AP has more than 4 neighbors is 55.3%, while that for 30 APs is 18.27%. This is mainly due to the fact that with more density of APs, the overlapping between the usage and interference areas from the APs also increases. Also, for a low density of APs, the probability that an AP has zero neighbors is greater than for a high density, so, for example, for 10 APs this probability is around 40 greater than for 50 APs.

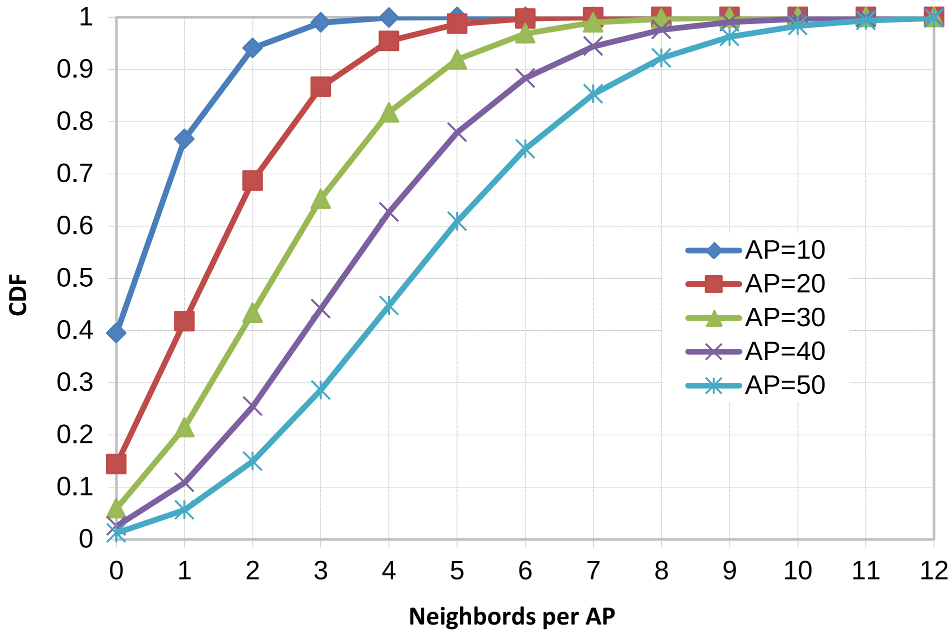


Figure 4.12: CDF of Number of Neighbors per AP

4.10.3 PB Channel Availability Characterization

In the proposed network scenario, the primary system considers channels with 5MHz of bandwidth and WLANs utilizing channels of 22MHz of bandwidth for both bands, which is why the maximum number of channels of 22 MHz in the primary band is 6, as shown in Figure 4.13. These 6 channels overlap each other. However, only two channels do not overlap, hence each AP could have up to 17 overlapping channels and 5 without overlapping.

Note that, to use a 22 MHz channel in the primary band, 5 available adjacent channels of 5 MHz are needed. Thus, for instance, the first effective channel in primary band that could be used by WLAN needs channels from 1 to 5 to be available.

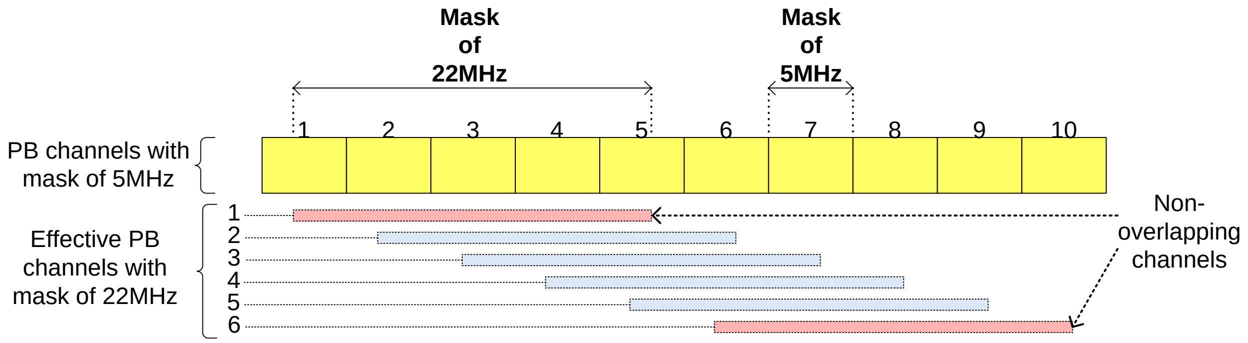


Figure 4.13: Effective Available Channels for WLANs in Primary Band

Figure 4.14 shows the channels used by PUs and the available primary channels for each AP in the network scenario in hexadecimal format. Thus, for instance, the APs far from the PUs have the ten primary channels available (i.e. 3FF= 1111111111). For ap_1, the available primary channels are 3F=0000111111 that corresponds to the channels 5, 6, 7, 8, 9, and 10 with mask of 5MHz. These channels represent two channels of 22MHz (i.e. channels 5 and 6 with mask of 22MHz).

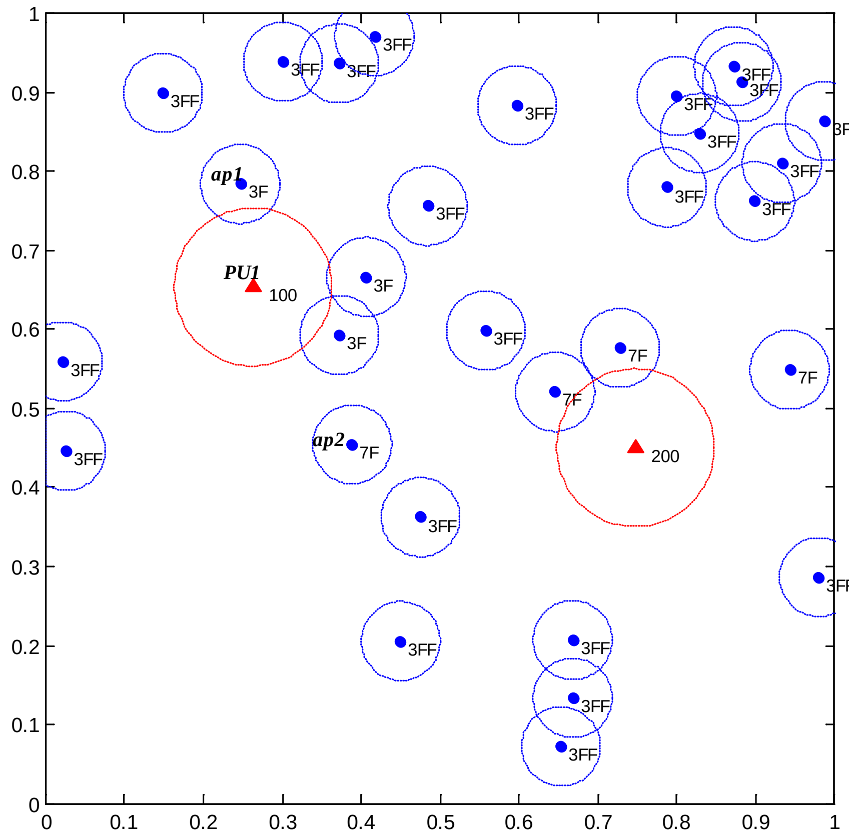


Figure 4.14: Available Primary Channels at each AP

The availability of primary band channels that can be potentially used by APs in the scenario under analysis is illustrated in Figure 4.15. Specifically, this Figure provides the probability distribution of the number of available channels per AP (expressed as a percentage) for different numbers of co-existing primary users. Hence, when 4 primary users are considered, the APs have about 55% of probabilities of disposing of the 100% of primary channels without impairing PU operation. On the other hand, if the number of primary users is set to 36, the probability that APs have full primary band availability is reduced to lees of 1.6% and, the probability that an AP does not have available primary channels is around 40%. . However, the probability that the APs take different values of percentage of available channels increase, i.e. the spectrum heterogeneity is also increased, so that if the number of PUs is increased, then the spectrum heterogeneity is also increased but the availability of primary channels at each AP is diminished.

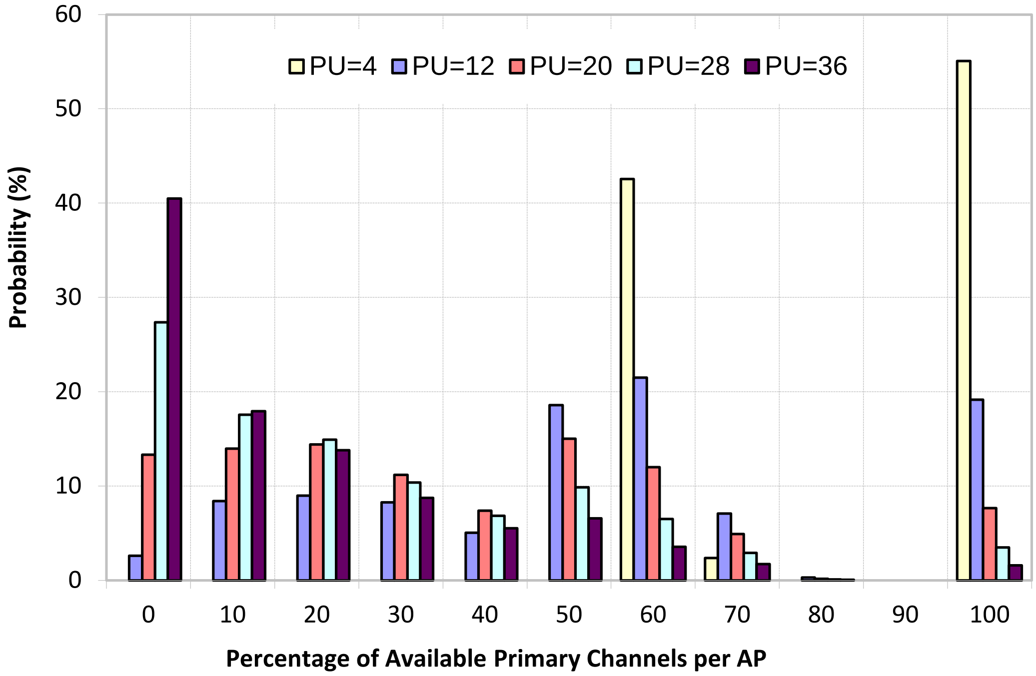


Figure 4.15: **Probability Distribution of the Number of Available Primary Channels per AP (expressed as a percentage of the full primary band) for Different Numbers of Co-existing Primary Users**

Figure 4.16 shows the percentage of available primary channels per AP versus the number of PUs in the scenario, for several usage radii of the primary system. This figure allows for the analyzing of the impact of the amount of users and usage areas of the primary system on the availability of primary channels in the scenario. The availability of primary channels decreases as the number of primary users increases in the scenario, For example, for 4 primary users the APs can obtain around 55 percentage points more of the available primary channels than for 36 primary users for a primary usage radio of 50 m.

Moreover, due to the direct relationship of the usage and interference radii of the primary system with the primary channel availability conditions, the availability of primary channels for the APs decreases as the primary usage radio increases; this is caused by the increasing of overlapping areas among devices.

Thus, for example for a primary usage radio of 25 each AP has an average of 19 percentage points more of available primary channels than for a usage radio of 100, for 12 PUs.

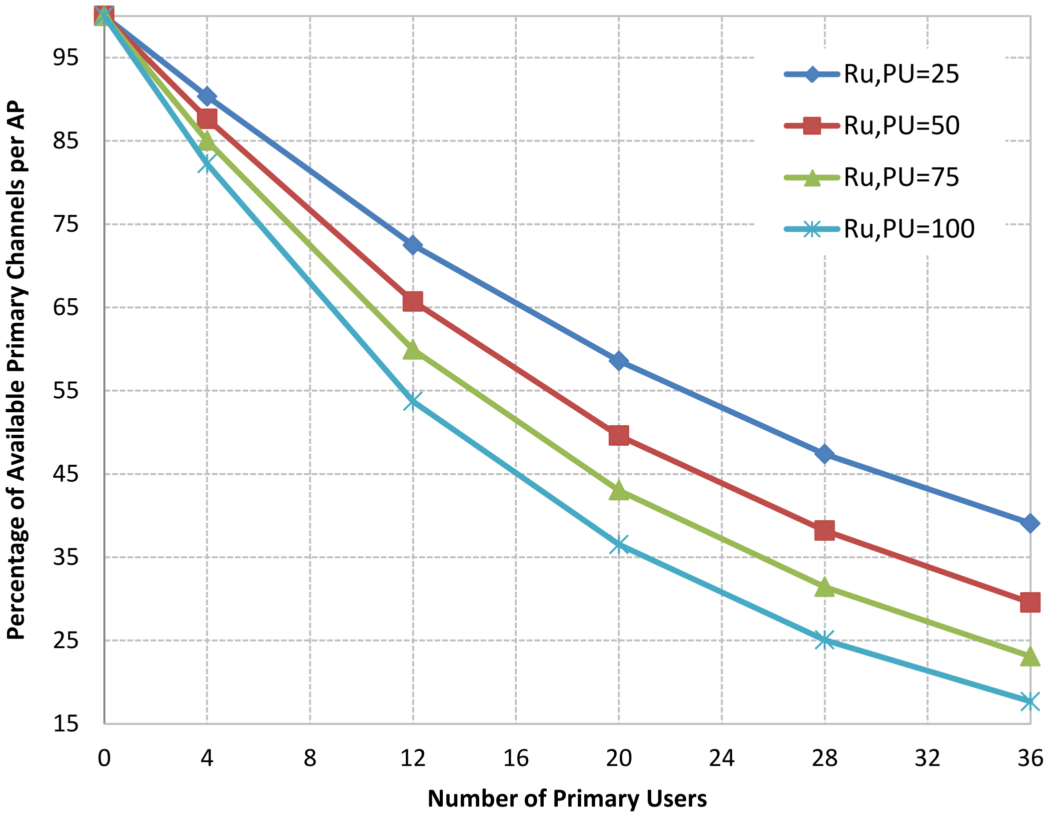


Figure 4.16: Percentage of Available Primary Channels per AP versus Number of Primary Users, for Different Usage Radius of PU, 30 APs and 5 PUs

4.11 Conclusions

In this chapter, network scenarios with OSA have been represented by means of a system model. By means of the proposed system model, a set of coverage and interference zones for each device in the scenario has been defined, and interference conditions for determining the primary channel availability have also been established, so that a list of available primary channels for each AP has been obtained. A new metric based on interference among devices has been defined. Constraint for the usage of the channel by APs was defined based on the penalties between APs; however these could be defined in terms of other network parameters. Definitions based on graph concept have been proposed. This model will be used in the following chapters to be used by channel assignment algorithms operating in an opportunistic environment.

Chapter 5. **Channel Assignments Algorithms in OSA-Enabled WLANs**

5.1 Introduction

In this chapter, a number of algorithms for solving the channel assignment problem for OSA-enabled WLANs are formulated and evaluated. Both centralized and distributed solutions are covered. When compared with existing algorithms used in conventional WLAN scenarios (cf. the state of the art discussion in Chapter 2), algorithms for OSA-enabled WLANs must cope with two new main distinguishing issues:

- Channel prioritization: channel selection criteria should not be based only on interference and load conditions of available channels, but should also consider the different regulatory constraints placed on ISM and OSA-enabled channels. As an example, under the same interference and load conditions, the use of an ISM channel may be preferred to the use of a primary band channel in order to decouple the channel assignment solution and the primary user activity as much as possible. Therefore, the channel assignment problem in OSA-enabled WLANs should consider additional priority criteria with regard to the selection of channels, in contrast with the common assumptions in place for the traditional WLAN channel assignment problem.

- Spectrum heterogeneity: channel availability might not be the same in each AP, since it depends on the location and activity of the PUs. This also makes the channel assignment problem different from the traditional problem, in which it is assumed that all APs have the same spectrum availability (i.e. the same set of ISM channels are available in all APs). Therefore, the OSA-enabled WLAN channel assignment problem must consider that not all the APs will have the same set of available channels for use.

The remainder of the chapter is organized as follows. Section 5.2 sets out the problem statement for OSA-enabled WLANs. Section 5.3 introduces the set of algorithms proposed in this thesis to cope with the channel assignment problem and discusses the rationale behind them. On this basis, Section 5.4 develops the formulation of the problem as a Binary Linear Problem (BLP), leading to the derivation of optimal solutions in Section 5.5. Finally, heuristic solutions for centralized and distributed computing approaches are developed and evaluated in Sections 5.6 and 5.7.

5.2 Problem Statement

Let's consider a dense deployment of APs with overlapping service/coverage areas. APs can always select to use a channel among those existing within the ISM band and, under some circumstances, a channel within an additional frequency band (e.g. primary band licensed to other services that is open for secondary access). The conditions for determining the availability of these additional primary channels are evaluated per AP so that APs can have different primary band availability according to the location and activity of the primary users (i.e. spectrum heterogeneity). The use of the same or adjacent channels in neighboring APs might lead to throughput reduction due to time sharing and interference increase in the used channels. In this respect, the penalty metric defined in Chapter 4 is used to model the suitability of using a given pair of channels in two neighboring APs. Therefore, spectrum availability per AP and channel assignment constraints (i.e. penalties between pairs of APs) are the inputs to the channel assignment mechanism, as illustrated in Figure 5.1.

On such a basis, the channel assignment problem consists of finding a proper channel assignment for every AP that satisfies two main objectives:

- The penalty between any pair of APs $P(ap_u^i, ap_v^j)$ is kept below a certain maximum penalty (P_{MAX}). This constitutes a channel assignment constraint aimed at mitigating throughput reduction due to time sharing and interference increase among neighboring APs.
- The number of APs using channels in the primary band is minimized. The rationale behind pursuing the minimization of primary band use is the need for channel assignments with low dependability on the presence of primary users. This objective is aimed at shielding as much as possible the WLAN operation from the temporal and spatial variations of the primary channels' availability.

A graphical illustration of the OSA-enabled WLANs channel assignment problem is depicted in Figure 5.1. As shown in the figure, the inputs to the channel assignment algorithm are obtained from the system model introduced in Chapter 4, which allows us to characterize the deployment scenario where WLANs and primary users coexist. Therefore, based on scenario-specific primary channel availability and channel assignment constraints, the channel assignment algorithm will choose the operational channel. The mechanism runs and tries to meet the established objectives. Finally, the obtained result is the assignation of one channel to each AP in the network scenario. These channels can be from ISM band or a certain primary band.

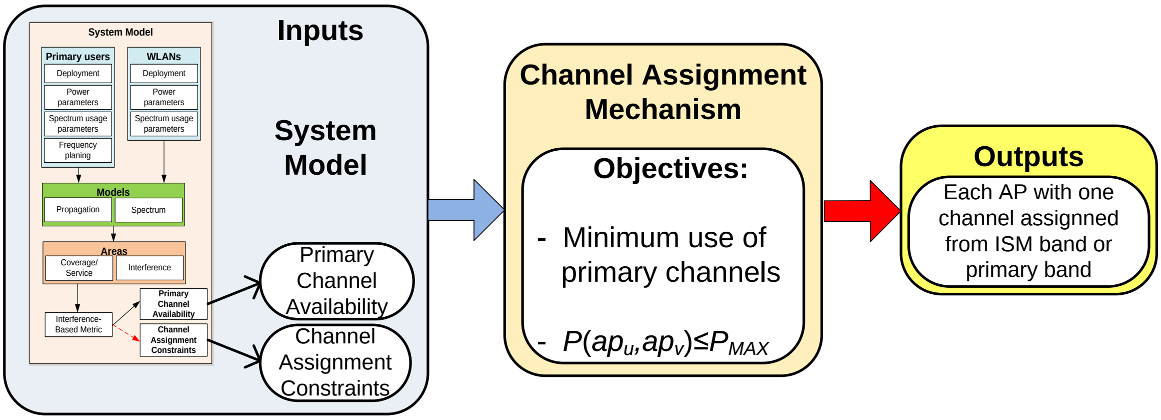


Figure 5.1: OSA-enabled WLANs Channel Assignment Problem

5.3 Proposed Solutions

The different approaches and algorithms developed in this thesis to solve the OSA-enabled WLANs channel assignment problem are illustrated in Figure 5.2.

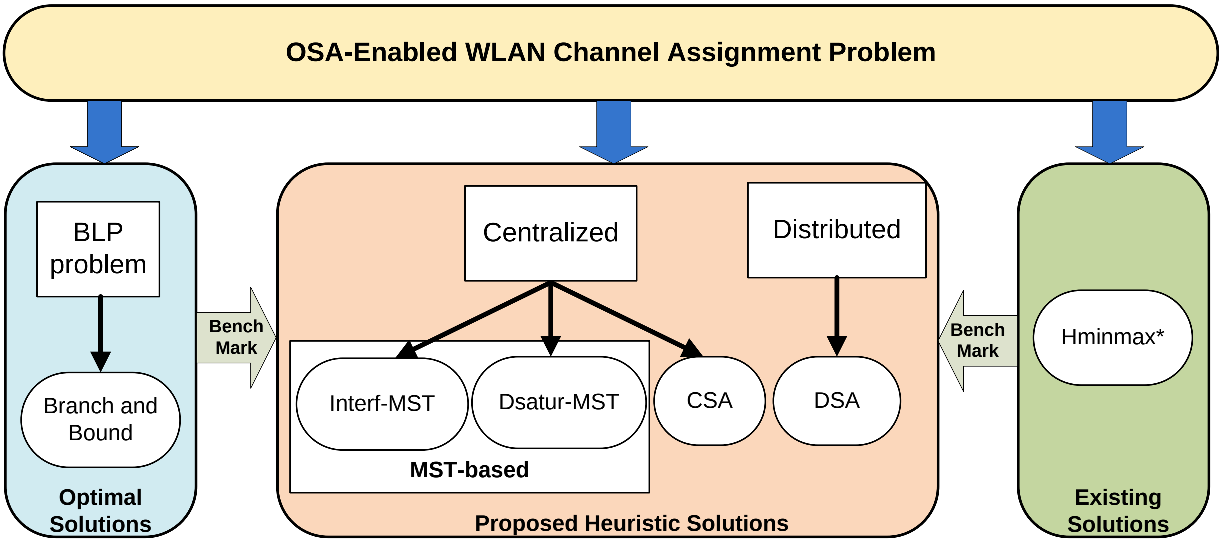


Figure 5.2: Proposals to Solve the OSA-enabled WLANs Channel Assignment Problem

One approach followed to tackle the problem was to formulate it as a Binary Linear Programming Problem (BLP), and Branch and Bound algorithms were used to obtain optimal solutions. Because of the high computational requirements, this approach is mainly used as a benchmark against which the other strategies can be evaluated under WLAN deployment scenarios with few APs.

Thus, motivated by the need to have computationally efficient solutions, a number of heuristic algorithms have been proposed and analyzed. Both centralized and distributed solutions were considered.

The proposed heuristic algorithms are built upon some outstanding channel assignment techniques proposed for conventional WLANs, which are extended and adapted to cope with the distinguishing elements of the OSA-enabled WLAN channel assignment problem.

In particular, for centralized computing, three heuristic algorithms are proposed (Interf-MST, Dsatur-MST and CSA). Two of them are based on building a Minimum Spanning Tree (MST) graph that accounts for the channel constraints admitted between APs and allows for the order used to assign the channel to the APS to be established. Where APs are represented as vertices, the edges between APs represent some degree of interference between APs. MST graphs are defined in terms of two factors: the primary channel availability and the penalty for Interf-MST, or the saturation degree (Dsatur), of each AP for the Dsatur-MST. Also, the mechanism used to determine the channel to be assigned to the APs only allows APs to assign a channel that improves the penalty perceived by them.

The third proposal for a centralized computing approach is a Simulated Annealing-based algorithm (CSA). CSA seeks to soften the restriction in place within the MST-based algorithms and expands the space of candidate solutions to avoid local optima. This algorithm allows for the channel being assigned to each AP to be chosen according to a set of probabilities. In particular, in CSA, a utility function based on the penalties is defined. This utility is inversely proportional to the sum of the penalties from all APs in the scenario, so that, in each iteration, if the utility is increased, then a new proposed channel is assigned to the AP; otherwise this channel is only assigned in accordance with a certain probability.

The problem is analyzed from the distributed computing approach. In particular, a distributed adaptation of the simulated annealing (DSA) algorithm is proposed for solving the problem. Thus, similar to CSA, DSA requires the definition of a utility function, but in this case it is only based on the local penalties of each AP. The process to determine whether a proposed channel is assigned to an AP is similar to CSA. The proposed DSA does not require exchanging information between APs (i.e., no coordination between APs).

Finally, in order to compare the proposed algorithms with existing mechanisms used in WLANs, an algorithm is adapted to operate with additional channels and to keep the same features that are currently used. In particular, an adaptation of the well-known Hminmax is developed. This adaptation is called Hminmax*.

5.4 Problem Formulation: Binary Linear Programming (BLP) Problem.

The channel assignment problem for OSA-enabled WLAN deployments can be formulated as a Binary Linear Programming (BLP) Problem. This allows us to compute the optimal solutions. The following notation is defined in order to formulate the BLP.

Let's denote $\mathbb{C}_T$ as the set of all potential channels. $\mathbb{C}_T$ comprises the subset $\mathbb{C}_{ISM}$, which contains C_{ISM} channels and the subset $\mathbb{C}_{PB}$, which contains C_{PB} channels in a PB. The channels are numerated so that the first channels, that is $i = 1, \ldots, C_{ISM}$, correspond to those in the ISM band and the subsequent ones, that is $i = C_{ISM}+1, \ldots, C_{ISM}+C_{PB}$, are the primary band channels.

The set of available channels (i.e. those that can be used without impairing the operation of primary users) for ap_u is represented by a NxC_T matrix A where A(ap_u, i)=1 if channel i is available for use at ap_u, and, otherwise, A(ap_u, i)=0. Notice that ISM channels are always available while PB channel availability will depend on primary user activity and interference conditions, as formulated in Section 3.3.1.

Hence, the channel selection for a given AP ap_u is represented by means of binary variables defined as:

$$x_{ap_u,i} = \begin{cases} 1 & \text{; if } i \text{ is assigned to } ap_u \text{ and } A(ap_u, i)=1 \\ 0 & \text{; otherwise} \end{cases} \quad (5.1)$$

According to previous notation and considering a scenario with N APs, the BLP formulation for the channel assignment problem can be represented as follows:

$$\min\left(\sum_{u=1}^{N}\sum_{i=C_{ISM}+1}^{C_{ISM}+C_{PB}} x_{ap_u,i}\right) \quad (5.2)$$

Subject to the following constraints:

$$\sum_{i=1}^{C_{ISM}+C_{PB}} x_{ap_u,i} = 1; \quad \forall u = 1, 2, \ldots, N \quad (5.3)$$

$$x_{ap_u,i} + x_{ap_v,j} \leq 1 \text{ if } P(ap_u^i, ap_v^j) > P_{MAX} \quad (5.4)$$

$$\begin{aligned} &\text{for} \\ &u, v \in \{1, \ldots, N\} \\ &i, j \in \{1, \ldots, C_{ISM} + C_{PB}\} \end{aligned} \quad (5.5)$$

in which (5.2) represents the objective function that minimizes the use of the primary channels. Constraint (5.3) indicates that a single channel is used per AP. Expression (5.4) accounts for the channel assignment constraint between each pair of APs. This constraint ensures that channels i and j cannot be assigned to AP u and v, respectively, when the penalty factor between them is higher than P_{MAX}. Expressions in (5.5) delimit the size of the sets of AP channels.

A solution to the BLP problem is said to be feasible if expressions (5.3) and (5.4) are satisfied. Then, the optimal solution is that which among the feasible solutions minimizes (5.2). Notice that the addressed BLP might admit more than one optimal solution.

5.5 Optimal Solution

BLP problems can be solved by using BB algorithms capable of finding optimal solutions, if the problem is feasible. However, in a previous work [77], we showed that such algorithms require a high computational effort compared with heuristics, which otherwise have been proven to obtain reasonable results for dense deployments with reduced complexity.

A measure of the complexity in solving these problems could be the total number of variables (i.e. $x_{ap_u,i}$) required to obtain optimal solutions that are given by $N \times (C_{ISM} + C_{PB})$, so for instance, for N=100, C_{ISM}=11, and C_{PB}=6, such number of variables is 6600. Therefore, in scenarios with a high density of APs, finding optimal solutions to the channel assignment problem requires very high computational efforts. In any case, branch and bound algorithms are used as a benchmark for performance evaluation of the proposed heuristics addressed in the following.

Branch and Bound (BB) algorithm [76] creates a search tree by repeatedly adding variables with their possible values to the problem; this process is known as a branching function. This function chooses a variable $x_{ap_u,i}$ and adds the value $x_{ap_u,i}$ = 0 to form one branch and the value $x_{ap_u,i}$ = 1 to form the other branch. This process can be represented by a binary tree as shown in Figure 5.3, in which the nodes represent a partial solution to the BLP problem with the current values of each variable. In each node, the algorithm decides whether to branch or to move to another node, depending on the outcome. This process is known as a bounding function, which estimates the best value of the objective function (5.2) obtainable by growing a node with a partial solution, either feasible or unfeasible, i.e. whether or not it meets constraints (5.3) and (5.4).

Hence, considering the above functions, if the BLP problem at the current node is unfeasible or its optimal value is greater than that of the best solution from a previous node, the algorithm removes the node from the tree, after which it does not search any branches below that node. Then the algorithm moves to a new node. Also, if the algorithm finds a new feasible solution with a lower objective value than that of the best solution from a previous node, it updates the current best solution node and moves to the next node. The algorithm stops when there are no nodes remaining for possible expansion.

Note that the main idea in branch and bound is to avoid growing the whole tree as much as possible, because the entire tree is just too big in any real problem. Thus, in the use of the proposed OSA-enabled WLANs channel assignment problem, the maximum number of solutions that the tree can generate is given by $2^{N \times (C_{ISM} + C_{PB})}$, where the exponent corresponds to the total number of variables. If the assumed values in the above example are considered, the maximum number of solutions that can be generated by the tree is 6.28×10^{1986}. Therefore, in scenarios with a high density of WLANs, finding optimal solutions to the channel assignment problem can require very high computational efforts.

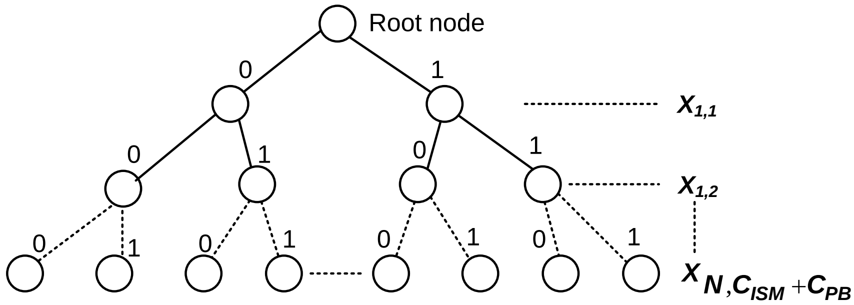


Figure 5.3: Binary Tree

5.5.1 Performance Evaluation

To solve the BLP problem, the BINTPROG function from the optimization toolbox provided by MATLAB is utilized. BINTPROG is based on the Branch and Bound (BB) algorithm.

The BINTPROG function has some configurable fields that limit the extensions of the search tree. A central parameter is its execution time, so that if the algorithm does not find a solution within that time, execution is stopped. Thus, according to the established execution times, BINTPROG can come up with different types of solutions:

- Optimal: the tree has been fully extended within the set execution time, and one optimal solution is found.
- Feasible: the tree has not been completely extended within the set execution time, but a feasible solution is available, that is, the optimal one over the searched part of tree.
- Unfeasible (tree fully extended): the tree has been fully extended within the set execution time, and no feasible solution has been found.
- Unfeasible (tree not fully extended): this accounts for the unfeasible solutions found when the tree has not been completely extended within the set execution time.

In this study, the execution time of the BB algorithm is set to one hour, thirty minutes and fifteen minutes, as a practical configuration to be used.

Notice that, just as in ISM channels, contiguous PB channels are partially-overlapping channels when used for WLAN transmissions since WLAN signals are assumed to be spread over 22MHz. Scenario configurations and simulation parameters used in these simulations are shown in Table 4.1and Table 5.1.These values will be used in the remainder of this chapter.

The provided results were obtained from 2000 snapshots and evaluated by using MATLAB. A computer with processor Intel Core 2 Quad of 2.4GHz and 5.9GB of RAM has been used for these simulations.

Table 5.1: Simulation Parameters

Parameters	Value
Number of Snapshots	2000
Number of Primary Users, PU	20
Usage Radio of PU	5m
Usage Radio of AP	5m
Interference Radio from SU to PU	184.1m
Interference Radio from PU to SU	96.53m
Interference Radio from AP to AP	75.8m

Figure 5.4 provides the percentage of the different types of solutions obtained by the BB algorithm when considering different densities of APs, twenty primary users, and three execution times. From this figure, when the complexity of the scenario is augmented by an increment of APs, then the amount of feasible scenarios decreases. For instance, for 24 APs and 1 hour, around 6 percentage points more of feasible scenarios are obtained than for 32 APs. For 24 APs, all analyzed scenarios have obtained solutions where the whole tree has been analyzed; therefore, these results are considered definitive. This is not the case for solutions obtained from deployments of 28 and 32 APs, where the execution times were not enough to check the whole tree.

Also, it is observed that for 28 APs, the amount of optimized scenarios is the same for the three configurations of execution time. The amount of feasible solutions obtained by a configuration of 1 hour are slightly larger than others due to the fact that it was possible to extend the tree a little more and to find more solutions that meet the constraints, of course, without minimizing.

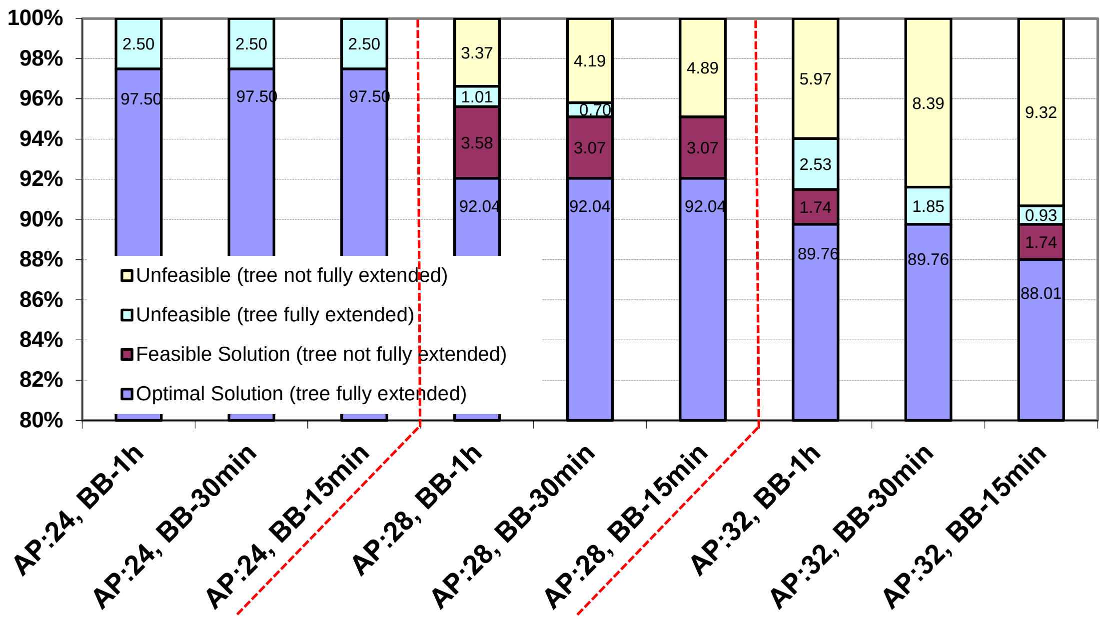


Figure 5.4: Percentage for Each Type of Solution Obtained by the Branch and Bound Algorithm

The average running time that the algorithm requires for finding the solutions is shown in Figure 5.5. From this figure, it is important to note the sharp rise in the time required to find a solution is caused by the increase of APs in the simulation scenario. So, for instance, this occurs when passing from 28 to 32 APs, and an execution time parameter of one hour, where this increase is around 534.31 percentage points.

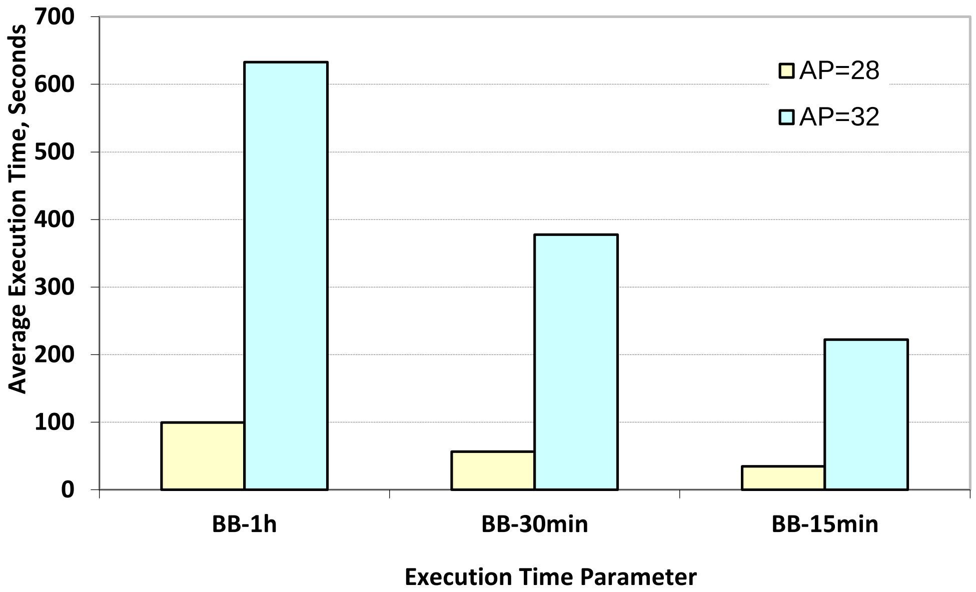


Figure 5.5: The Average Execution Time to Achieve an Optimal Solution Using BB Algorithm

5.6 Centralized Computing Solution

Three computationally-efficient centralized algorithms are proposed and evaluated in this section: Interf-MST, Dsatur-MST and CSA.

The former two are based on the building of a Minimum Spanning Tree (MST) for determining the order in which APs are assigned to their corresponding channel. Then, the method used to choose the channel to be assigned to each AP is based on an adaptation of the Hminmax algorithm. After an initial evaluation of the two MST algorithms, these are modified to support an iterative mode with channel reassignment capabilities (called iterative variants).

The third proposal is already an iterative algorithm based on simulated annealing (SA) techniques, which utilize stochastic mechanism to assign the channel to each AP.

5.6.1 MST-based Algorithms

Heuristic algorithms for channel assignment are generally split into two subproblems: 1) the list ordering the APs and 2) channel selection in each AP, by following the ordered list.

Figure 5.6 shows a reduced scheme of the proposed algorithms.

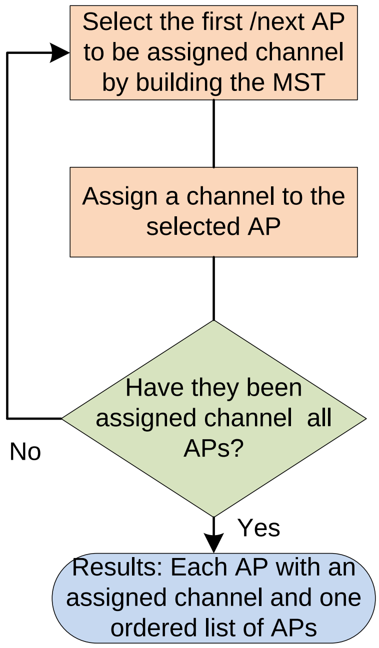


Figure 5.6: Reduced Scheme of the Proposed Non-Iterative Algorithms

To determine the order, these mechanisms are built upon weighted graph coloring techniques, which have already proven to be efficient for the classical channel assignment problem, so that the order in which each AP is colored depends on the weight of the edges among APs. Thus, in order to establish an ordered list with the sequence in which the APs will be colored, and in which the sum of the weights of the edges between APs according to the ordered list is as small as possible, a Minimum Spanning Tree (MST) problem is formulated.

A spanning tree of a graph is a sub-graph, which is a tree, and connects all the nodes together. A single graph can have many different spanning trees. A graph is extended by assigning a weight to each edge of the graph. Hence, an MST is a spanning tree with a weight less than or equal to the weight of every other spanning tree. The weight is defined below.

The algorithm is based on Prim's algorithm to find the MST of a given graph [101]. Therefore, the problem becomes: given a connected graph G and a weight W: $E \rightarrow R^+$, an MST is found and, while doing so, a channel is chosen for new APs joining the MST. Consequently, the resulting MST is the one containing the lowest sum of weights between APs.

In particular, in this section, two MST-based heuristic algorithms are proposed. The only difference between the two algorithms is the computation of the graph's weights. Thus, the first proposal is based on the interference levels between APs, and the second is built on the saturation degree (Dsatur) at the APs.

On the other hand, in both algorithms, the mechanism used to choose the channel for each AP takes into account the minimization of the number of APs using primary channels and the channel assignment constraints. This is based on the Hminmax algorithm and is described later.

Interference-based MST

In this algorithm, the weight of an edge (ap_u,ap_v) with direction from ap_u to ap_v is defined in terms of a channel availability factor at AP *v*, referred to as $\lambda\left(ap_v\right)$, and the penalty metric *P*(defined in section 4.6) between APs *u* and *v* in co-channel conditions, according to the following expression:

$$W\left(ap_u, ap_v\right) = \lambda\left(ap_v\right) \cdot P\left(ap_u^i, ap_v^i\right) \tag{5.6}$$

λ is formulated as a decreasing function of the number of available primary channels at a certain AP. Therefore, the lesser the number of primary channels available for use by an AP, the higher the value of the factor λ assigned to this AP. This factor will allow the channel assignment algorithm to exploit the spectrum heterogeneity by increasing the weight associated with APs with less available primary channels (i.e. these APs will increase their probability of being assigned first since they have more restrictions).

In this work, factor λ is computed by using the following decreasing exponential function:

$$\lambda\left(ap_v\right) = e^{-s \cdot \left(\sum_{\forall j \in \mathbb{C}_{PB}} A(ap_v, j) \right)} \tag{5.7}$$

where a slope parameter *s* is used to adjust the level of sensitivity to the number of available primary channels in AP *v*. In the case that the spectrum heterogeneity feature is not exploited, λ is simply set to 1. Note that, if spectrum heterogeneity is exploited, the weight between two APs is asymmetric i.e. $W(ap_u,ap_v) \neq W(ap_v,ap_u)$ if the two APs have different primary channel availability.

Figure 5.7 provides the pseudocode for building the MST. As shown in this figure, the input parameters of the algorithm are: the sets of vertices (*V*), edges (*E*) and available channels (*A*) for each AP**,** and the value of the channel availability factor λ of each AP. The exploitation of channel prioritization for the channel assignment is also considered as an input parameter. In this way, the same algorithm can be configured to prioritize or not the utilization of the ISM band. This is indicated by means of the flag *Prior*∈{*True*, *False*}, where if *Prior*=*True*, then the prioritizing of the ISM band is considered. The results achieved by the algorithm are a minimum spanning tree composed of a set of edges (E_n), a set of APs (V_n) corresponding to an ordered list with the sequence in which each AP is colored, and for each $ap_{u,,}$ its corresponding assigned channel $Ch(ap_u)$.

The algorithm starts by choosing the AP that has the lowest product of the channel availability factor and sum of penalty with respect to its neighboring APs. This AP is called ap_x. (line: 1-2). This is a way to initialize the algorithm while maintaining the same approach used to define the weight.

The channel to be assigned to the first AP $Ch(ap_x)$ is computed by the function "Assign Channel" that is explained later (line: 3). Next, the AP is included in the vector of assigned channels so that $V_n=\{ap_x\}$ (line: 4).

Then, the next AP chosen for channel assignment is the one that has the edge with the largest weight with respect to all the other APs with channels assigned (line: 6-7). If two or more APs have the same value of weight, then the next AP chosen for channel assignment follows an arbitrary order. The AP chosen is called ap_y, and the channel assigned $Ch(ap_y)$ is determined by the function "Assign Channel" (line: 8).

Next, the ap_y is included to V_n and the first edge of the MST is generated so that (ap_x,ap_y) is added to E_n (line: 9). The algorithm repeats this process until all N APs have been assigned a channel (i.e. $|V_n|=N$) (line: 5).

Algorithm: **MST**
Data: A connected weighted graph with vertices *V* and edges *E*, *A*, λ, *Prior*.
Result: Minimum spanning tree composed of V_n and E_n where each $ap_u \in V_n$ has a assigned channel $Ch(ap_u)$.
1. $L(ap_u) \leftarrow \lambda(ap_u) \cdot \sum_{\forall\, ap_v \in B(ap_u)} P(ap_u^i, ap_v^j)$; $\forall\ ap_u \in V,\ \wedge\ i=j$
;$L(ap_u)$ is the product of: Availability of primary channels at AP *u* and sum of all penalties between AP *u* and all other APs, for co-channel conditions
2. choose ap_x as the first AP such that:
$L(ap_x) = \max(L(ap_u))$
; If two or more APs are in the same situation then the AP is randomly chosen among them.
3. **Assign Channel**; call the function to assign channel to ap_x
4. Update the vector of APs with channel assigned, $V_n=\{ap_x\}$
5. **while** $\lvert V_n \rvert \leq N$
6. $M(ap_v) \leftarrow \max(W(ap_u, ap_v))$; $\forall\ ap_u \in V_n, ap_v \in \{V - V_n\}$
;$M(ap_v)$ is the Max weight from any AP with a channel assigned to all other APs without channels assigned.
7. choose ap_y as the next AP such that:
$M(ap_y) = \max(M(ap_v))$
; If two or more APs are in the same situation then the AP is randomly chosen.
8. **Assign Channel**; call the function
9. **add** ap_y to V_n , and (ap_x, ap_y) to E_n
10 **end**(5)

Figure 5.7: Pseudocode to Build the MST

Channel Assignment

The required pseudocode to implement the function "Assign Channel" is shown in Figure 5.8. The input parameters are: *Check_PB*, and *Prior*.

The function begins identifying whether the ap_u to be analyzed has neighbors with assigned channels (line: 1).

If the AP does not have neighboring APs with assigned channels, the channel to be assigned is chosen from among the non-overlapping channels from the ISM band (i.e. channels without overlap in accordance with the 802.11 standard), such that the channel assigned to ap_u is defined as $Ch(ap_u)$ (line: 2).

Otherwise, the algorithm first tries to find a valid channel in the ISM band, in accordance with the goal of minimizing primary band utilization represented in the BLP problem by (5.2) (line: 4-5). The obtained channel is denoted as C_S. This one minimizes the maximum interference between the AP u and its neighbors in order to try to meet constraint (5.4) of the BLP problem (line: 5).

If the prioritization of the ISM band is considered (i.e. *Prior*=*True*) and the maximum P between the AP u using c_s and any of its neighbors is equal to or lower than P_{MAX}, or the AP u has no available primary channels, then channel c_s is assigned to the AP u (line: 6), unless the AP y has available primary channels, then the flag *Check_PB* is fixed to *True* (line: 7), and the algorithm is readied to look for a channel in the primary band (line: 9).

In such cases, the algorithm finds a primary channel candidate to be used (denoted as c_p). If it exists, the primary channel will be assigned when the maximum P is satisfied between neighbors also using channels from the primary band (line: 9-12). Otherwise, the algorithm chooses the channel with the least interference in either of the two bands (line: 13-14).

Notice, as in constraint (5.3) of BLP problem formulation, only one channel can be assigned per AP; this fact is considered in the algorithm in (line: 6, 12, 13, and 14). Moreover, if in (line: 6) and (line: 12) *Prior*=*False*, then the algorithm does not try to prioritize the use of the ISM band for minimizing the use of PB.

Saturation Degree-based MST

In this algorithm, the weight of an edge (ap_u,ap_v) with direction from ap_u to ap_v is defined in terms of the channel availability factor $\lambda(ap_v)$, and the saturation degree at the ap_v, as shown in the following expression:

$$W(ap_u, ap_v) = \lambda(ap_v) \cdot SD(ap_v) \tag{5.8}$$

where SD is the saturation degree at ap_v, which corresponds to the number of neighboring APs with assigned channels. Notice that, in this context, the ap_u is already assigned a channel and the ap_v not yet.

The input parameters and considerations for building the MST are the same as those used by Intef-MST so that Dsatur-MST can be developed by using the pseudocode shown in Figure 5.7, but with some modifications as detailed below:

- The weight defined in (5.8) for Dsatur-MST has to be used for the computing
- In order to obtain the initial AP, line: 1 is replaced by:

$$L\left(ap_u\right) \leftarrow \lambda\left(ap_u\right) \cdot \left|B(ap_u)\right|; \forall ap_u \in V$$

;$L(ap_u)$ is the product of: Availability of primary channels at AP u, $\lambda(ap_u)$ and the number of neighbors of the AP u, i.e. $|B(ap_u)|$.

Function: Assign channel

Data: ap_u, V, V_n, E, *Check_PB*, *Prior*, A

Result: AP u with an assigned channel $Ch(ap_u)$.

1. **if** $\left\{B\left(ap_u\right) \cap V_n\right\} = \varnothing$

;if ap_u has not neighbors with assigned channel

2. $Ch(ap_u) = rand\,\{1,6,11\}$

;choose randomly from ISM band one non-overlapping channel for assignning to theAP u

3. **else**

4. $H(c) \leftarrow \max\left(P(ap_u^c, ap_v^{Ch(ap_v)})\right);\ \forall\ e = (ap_u, ap_v) \in E;\ c, Ch(ap_v) \in \mathbb{C}_{\text{ISM}};\ ap_v \in V_n$

; $H(c)$ is max P of any edge respect to ap_u, considering only ISM band

5. Choose c_s such that:

$H(c_s) = \min_{c \in \mathbb{C}_{\text{ISM}}} H(c)$

;choose color with the min(max.P) between ap_u and its neighbors using ISM band

6. **if** (*Prior*=*True* and $H(c_s) \le P_{MAX}$) or $\sum_{\forall i \in \mathbb{C}_{PB}} A(ap_u, i) = 0$;$Ch(ap_u) \leftarrow c_s$

;if prior is true the channel c_s is directly assigned

7. **elseif** $\sum_{\forall i \in \mathbb{C}_{PB}} A(ap_u, i) > 0$; *Check_PB*=*True*

;look if the AP u has available primary channels

8. **end**(6)

9. **if** (*Check_PB*=*True*)

;look within the PB if the achieved P in the primary band exceeds the maximum penalty

10. $H(c) \leftarrow \max\left(P(ap_u^c, ap_v^{Ch(ap_v)})\right);\ \forall\ e = (ap_u, ap_v) \in E,\ c, Ch(ap_v) \in \mathbb{C}_{\text{PB}}$

; $H(c)$ is the max P of any edge respect to ap_u using the channel c, considering only PB

11. Choose c_p such that:

$H(c_p) = \min_{c \in \mathbb{C}_{\text{PB}}} H(c)$

;choose color with the min (max P) between ap_u and its neighbors using PB

12. **if** *Prior*=*True* and $H(c_p) \le P_{MAX}$; $Ch(ap_u) \leftarrow c_p$

13. **elseif** $H(c_s) \le H(c_p)$; $Ch(ap_u) \leftarrow c_s$;

;if the H is the same for both bands then ISM band is chosen

14. **else** $Ch(ap_u) \leftarrow c_p$;

15. **end**(12)

16. **end**(9)

17. **end**(1)

Figure 5.8: Pseudocode of the function "Assign Channel"

Thus, following Figure 5.7, since no vertex has been initially colored, the first AP chosen for channel assignment, ap_x is the AP with the highest product of number of neighbors (i.e. not colored) and reduced availability of primary channels (line: 1-2). The channel assigned to ap_x is determined by the function "Assign channel", (line: 3). Thus, the vector of APs with assigned channels is updated, $V_n=\{ap_x\}$ (line: 4). The remainder of the pseudocode is performed in the same manner as the one described above.

Illustrative Example of Building the MST

Figure 5.9 shows an example for building both the Interf-MST and the Dsatur-MST. Here, it is assumed that the number of available primary channels is the same for all APs. Hence, the weight directly corresponds to the penalty between APs and the saturation degree at the APs for the Interf-MST and the Dsatur-MST respectively. Also, three non-overlapping channels are considered for assignment to APs (i.e. 1, 6, 11). Figure 5.9a shows the weight used for each edge.

Hence, the Interf-MST is built by following the pseudocode shown in Figure 5.7. The first AP corresponds to the one with the maximum sum of penalties in co-channel conditions, in this case the ap_1. The channel chosen for this AP is obtained by using the pseudocode for the function Assign Channel from Figure 5.8. Hence, since this AP has no neighbors with assigned channels, the channel is randomly chosen from the non-overlapping channels of ISM band, in this example, we suppose channel 1 as shown Figure 5.9b.

From ap_1, the AP with the highest weight is ap_2, so this AP is chosen to extend the tree, as shown in Figure 5.9b. For this AP, the channels 6 and 11 are possible candidates, given that both provide the min(max.*P*) between ap_2 and its only neighbor ap_1 using ISM band, assuming that channel 6 is randomly chosen.

Then, from ap_1 and ap_2, the AP with the maximum weight of any of them is ap_3, so that the tree is extended to this AP as shown in Figure 5.9 c. Given that ap_3 has two neighbors with assigned channels (i.e. 1, 11), the only available channel to be assigned is 11.

Finally, the tree is extended to ap_4 and the MST has been completely built, as depicted in Figure 5.9d. As for ap_2 the channel is randomly selected between channels 6 and 11, given that ap_1 uses channel 1, so, for example, channel 6 is chosen.

For building Dsatur-MST, following the pseudocode shown in Figure 5.7 and the modification described in *Saturation Degree-based MST,* the first AP corresponds to the one with the maximum number of neighbors, in this case, ap_1. The choice of channel is performed similarly to Interf-MST, so that it is assumed that channel 1 is assigned.

The APs ap_2, ap_3, ap_4 have the same saturation degree (i.e. *SD*=1), so that the next AP is arbitrarily chosen from these APs. Assume that ap_3 is chosen to extend the tree, as shown in Figure 5.9e. For this AP, channel 6 is assigned.

Then, from ap_1 and ap_3, the *SD* with respect to ap_2 is 2 and ap_4 is 1. Hence, the AP with the maximum *SD* is ap_2, so that the tree is extended to this AP as shown in Figure 5.9f. Assume that the assigned channel is 11.

Finally, the ap_4 with *SD*=1 is selected for channel assignment. Thus, the tree has been completely built, as depicted in Figure 5.9g. In this case, the channel to be assigned to the ap_4 is randomly chosen from between 6 and 11; assume that channel 11 is selected.

Note that, the tree built for Dsatur-MST differs from the one obtained for Interf-MST, because these two proposals have different weight definitions.

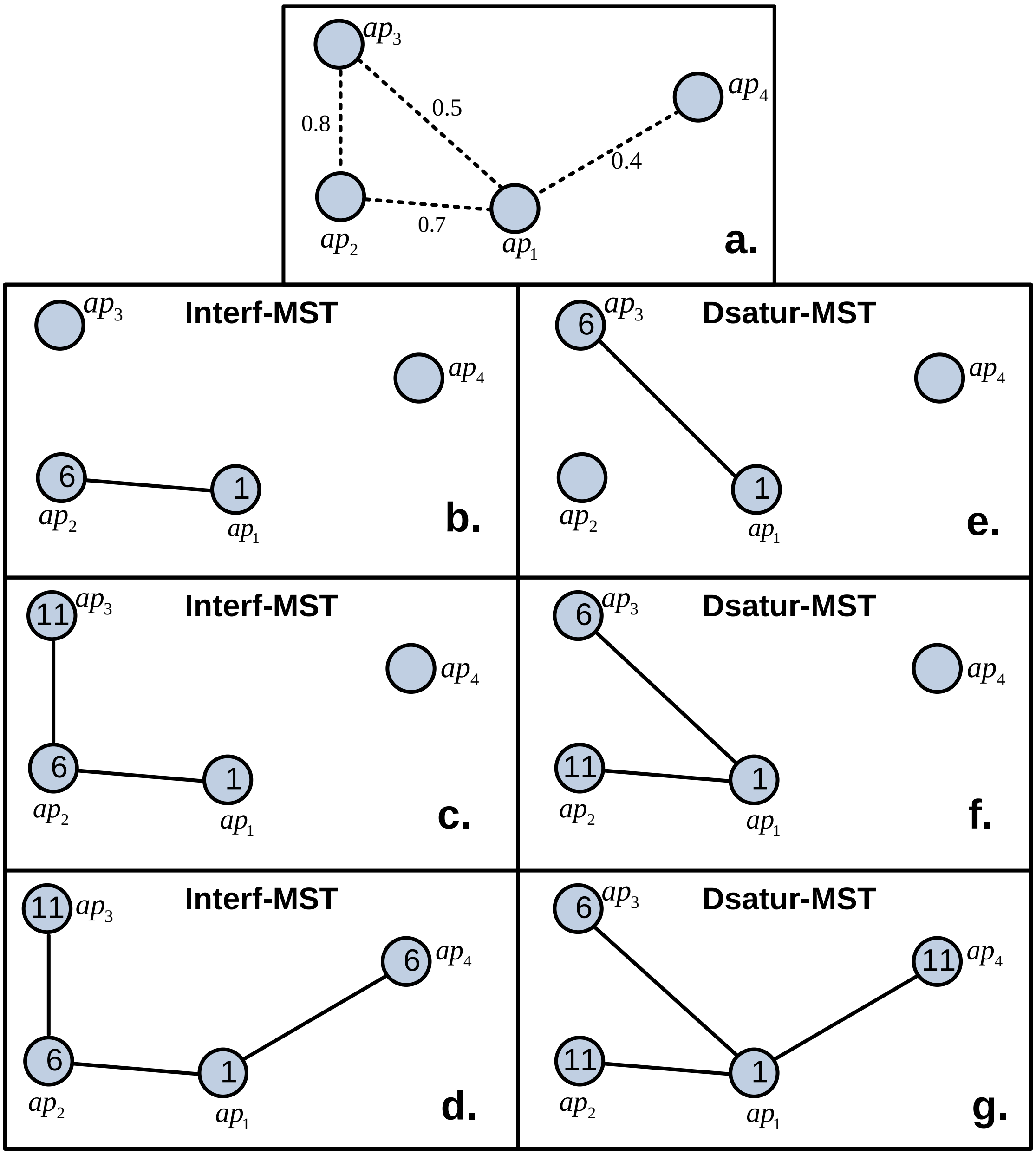


Figure 5.9: Example of the Building of the MST

Iterative Version

Enhanced versions of the MST algorithms have been obtained by allowing the algorithms to be used in an iterative manner. Figure 5.10 shows a schematic of this enhancement.

As shown in this figure, the order in which each AP is analyzed to be reassigned to its operation channel is obtained from an ordered list of APs generated by building the MST in the non-iteractive algorithm.

This channel reassignment is performed for each AP. However, if the penalty obtained by the current channel is less than or equal to that achieved by the proposed channel from the reassignment, then the channel is not changed. This procedure is repeated until all the APs have been reassigned channels, if needed. The channel reassignment is performed by the function Assign Channel described in Figure 5.8.

Having analyzed all APs, it is then analyzed whether the state of convergence has been reached. If so, the algorithm stops. Otherwise, the number of iterations increases and the reassignment procedure is repeated. The convergence criterion is defined later.

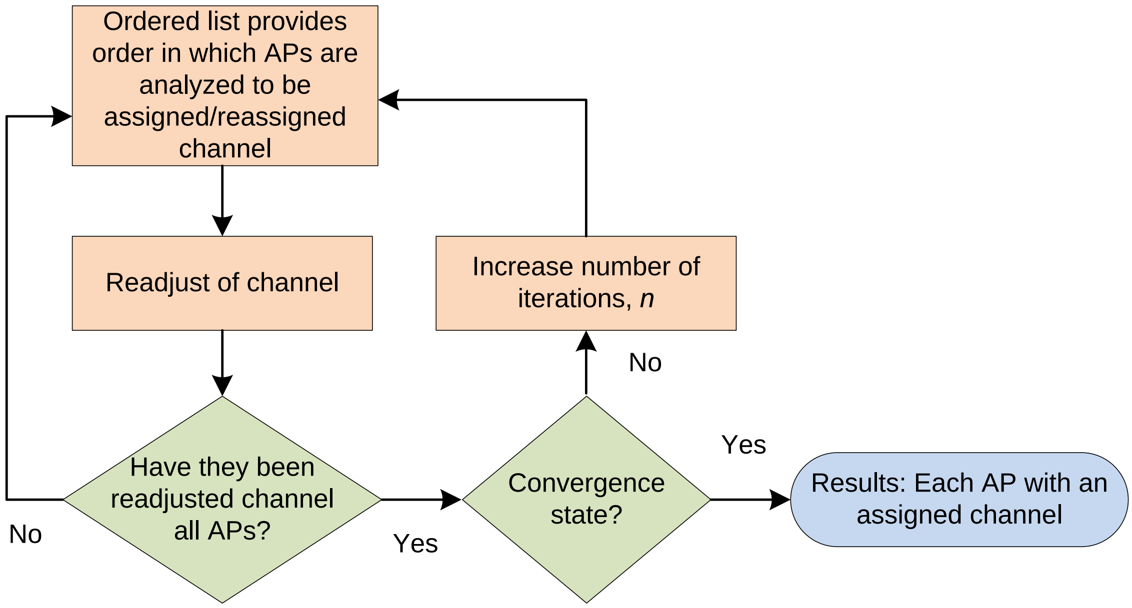


Figure 5.10: Reduced Scheme for Implementing Iterative Algorithms

At each iteration, the algorithm finds a percentage of APs with all their edges with P below P_{MAX} from all APs on the network scenario. This value is denominated as the percentage of feasible APs (%FAP). Hence, the variation between the percentage of feasible APs obtained at the current iteration (%FAP_n) and the previous iteration (%FAP_{n-1}) is computed as follows:

$$\Delta_n = \frac{\left|\%FAP_n - \%FAP_{n-1}\right|}{\max\left(\%FAP_n, \%FAP_{n-1}\right)} \tag{5.9}$$

with n being the number of the current iteration.

In this way, the convergence state is reached when the variation of feasible APs at the current iteration minus the average obtained from *r* previous variations is less than or equal to a certain allowed minimum value of variation (*Q*). This criterion is computed by the following expression:

$$\text{Convergence State: } \Delta_n - \frac{\sum_{m=n-1}^{n-r} \Delta_m}{r} \leq Q \qquad (5.10)$$

In this thesis, this criterion is applied for all the iterative algorithms.

5.6.2 Centralized Simulated Annealing

This section proposes an algorithm based on SA techniques to solve the OSA-enabled WLAN channel assignment problem. This algorithm is considered to be performed from a centralized viewpoint and is referred to as CSA (Centralized Simulated Annealing).

Simulated annealing techniques are iterative algorithms that require the definition of a utility function to be maximized. In our case, the utility is based on the penalties from all APs in the scenario. In each iteration, a new candidate channel is proposed to be assigned to each AP. If the utility is increased, then a new proposed channel is assigned to the AP; otherwise, this channel is only assigned in accordance with a certain probability.

Before the algorithm is described, certain mathematical notation is provided which allows for the adaptation of the proposed channel assignment problem with the structure of the simulated annealing algorithm. Hence, in the section below, the utility function and the candidate channel are defined, and then the algorithm is described in detail.

Total Utility Function

The maximum penalty resulting at ap_u from its neighbors when channel *i* is used is computed by means of the following expression:

$$MP_{ap_u}^{i} = \max_{\forall ap_v \in B(ap_u)} P\left(ap_u^i, ap_v^{Ch(ap_v)}\right) \qquad (5.11)$$

where, if $MP_{ap_u}^{i}$ is below the threshold $P_{MAX,}$ then channel *i* is considered as a feasible channel for the ap_u.

In accordance with the above definitions, for each AP, a utility function $U_{ap_u}^{i}$ is used to map $MP_{ap_u}^{i}$ values to the preference given to channel *i* by ap_u when looking for an operational channel. The utility function is a decreasing function with respect to the amount of *MP*, so that the lower the *MP* for a given channel, the higher the utility given to that channel. In particular, a sigmoid function defined as follows is used in our analysis [102]:

$$U_{ap_u}^i = \begin{cases} 1-(1-q)\cdot e^{s\left(MP_{ap_u}^i - P_{MAX}\right)}; MP_{ap_u}^i \le P_{MAX} \\ q.e^{-s\left(MP_{ap_u}^i - P_{MAX}\right)} \quad ;\text{otherwise} \end{cases} \tag{5.12}$$

where q denotes the utility value when $MP_{ap_u}^i = P_{MAX}$, and s determines the slope of the utility function.

So that, the total utility in the scenario is defined as the contribution from the utilities generated by each deployed AP and is defined by the following expression:

$$TU = \sum U_{ap_u}^i ;\forall ap_u \in V,\ i \in \mathbb{C}_T \tag{5.13}$$

To analyze the impact on the total utility when a given ap_u uses a certain channel i, the total utility is denoted as $TU_{ap_u}^i$. In such a case, the individual utilities for each AP are computed again considering the i channel assigned to the ap_u.

Therefore, the objective of the channel assignment problem is then set out to maximize the total utility. Hence, the channel assignment problem for the network scenario can be formulated as:

$$\text{maximize } (TU) \tag{5.14}$$

Subject to: ap_u only uses one channel at a time

Candidate Channel

To obtain a candidate channel for the ap_x, the algorithm assigns a probability to each available channel at the ap_x as shown in the following expression:

$$p_i = \frac{w_i}{\sum w_i},\ \forall i \tag{5.15}$$

being w_i the weight of each channel i.

In such a way, the following situations could be derived:

- If there is at least one feasible channel then $w_i = TU_{ap_x}^i$ for the feasible channels, and w_i=0 for unfeasible channels. Notice that, if $MP_{ap_u}^i \le P_{MAX}$ then the channel i is considered to be a feasible channel.
- Additionally, in the case that there is at least one feasible channel in each band, weights of the primary channels are multiplied by the band prioritization factor BP i.e., $w_i = BP \cdot TU_{ap_u}^i$, where $BP = [0,1]$.

- If the channels are not feasible, $w_i = TU^i_{ap_x}$. Notice that, when channels are not feasible, the priority for both bands is the same, so that the channels with more utility have a higher probability of being chosen.

Algorithm Description

The algorithm is executed by a central entity and allows for the selection of an operation channel for each AP, either from an ISM band or a primary band.

The pseudocode used for developing the CSA is shown in Figure 5.11. CSA parameters are set up i.e. initial temperature, T_0, cooling rate *CR*, and the predefined constant $\in$. The algorithm works as follows:

The algorithm computes initial channels and initializes the temperature. In particular for this, channel 1 is assigned for all the APs as the current operation channel (line: 1).

As the algorithm is executed iteratively, the stopping criterion is established in order to stop the algorithm. In particular, this algorithm has three stopping criteria, which are evaluated after analyzing all APs so that the algorithm is stopped by any of the following cases: 1) Number of iterations n_c: the maximum number of iterations $n_{c\text{-}max}$ is found. 2) Temperature *T*: The minimum temperature (T_{min}) is obtained, and 3) Convergence: The convergence state (i.e. established for iterative algorithms) is achieved (line: 2). Note that, for each iteration *n* used in the convergence criterion, all APs are analyzed in order to find a stable percentage of feasible APs in the scenario.

The algorithm analyzes, for each AP, if the current channel is maintained or changed (line: 3).

The APs are chosen to be analyzed; in this work, they are randomly selected. As shown in the figure, ap_x is the AP to be analyzed, and its current operation channel is denoted as *i* (line: 4).

Thereby, a new channel, *j*, is obtained as a candidate channel to be assigned to ap_x (line: 5). The manner in which the candidate channel is chosen has been previously described.

The decision to hold the current channel used by ap_x, *i*, or assign the candidate channel, *j*, depends on a comparison between the total utilities obtained by using those channels. Therefore, if $TU^i_{ap_x}$ is the total utility obtained with the current channel (i.e. *i*) at ap_x and $TU^j_{ap_x}$ with the candidate channel (i.e. *j*), then the candidate channel is assigned to the ap_x, if the utility is incremented, i.e. $\delta = TU^i_{ap_x} - TU^j_{ap_x} < 0$ (line: 6-8). If the candidate channel decreases the total utility, it will be accepted with probability depending on the change in the total utility δ and the current temperature *T*, $\Pr[\delta,T]=e^{-\delta/T}$ (line: 9-12).

On the other hand, if the candidate channel provides the same total utility as the current channel, it will be accepted with probability depending on the predefined constant, $\in$ and *T*, $\Pr[\in,T]=e^{-\in/T}$ (line: 13-16). Otherwise, the operation channel of ap_x does not change.

Once ap_x is anaylzed, this is added to the revised AP's vector, V_n (line 18), and the process is repeated until all APs are analyzed.

Note that, through this stochastic selection scheme SA can avoid being stuck at local optimum.

Then, T values are updated at each iteration (line: 20) and gradually decrease so that the probability of accepting a new channel that does not improve the total utility also decreases.

Algorithm: **CSA**

Data: Temperature T_0, CR, $\in$, V, E, N, T_{min}, Q
Result: max TU

1. Compute initial channels for all APs, $T = T_0$
2. **while** *stopping criterion* is not reached
; Verify if any $n_{c\text{-}max}$, T_{min} , or *convergence state* are achieved
3. **while** $|V_n| \leq N$
; this process is realized for all APs
4. ap_x
;next AP chosen to be analized with i as its current channel
5. Obtain new channel for ap_x, j
;j is a candidate channel
6. Compute $\delta = TU^{i}_{ap_x} - TU^{j}_{ap_x}$
7. **if** $\delta < 0$ **then**
8. $i = j$;
9. **elseif** $\delta > 0$ then
10. **if** *random*[0,1] < $e^{(-\delta/T)}$ **then**
11. $i = j$;
12. **end**(10)
13. **elseif** $\delta = 0$ then
14. **if** *random*[0,1] < $e^{(-\in/T)}$ **then**
15. $i = j$;
16. **end**(14)
17 **end**(7)
18. **add** ap_x to V_n
19. **end**(3)
20. Update $T = CR \cdot T$ and *number of iterations* (n_c)
21. **end**(2)

Figure 5.11: Pseudocode of the CSA Algorithm

Algorithm Used as Lower Benchmark

In order to obtain a benchmark for comparing the results obtained by the proposed algorithms, an algorithm currently used in WLANs for the channel assignment is adapted to operate with additional channels and keep the same features that it currently uses.

In particular, an adaptation of the Hminmax is developed [86]. This adaptation is referred to as Hminmax*. This one can be implemented by using the pseudocode illustrated in Figure 5.8 (i.e. Function Assign Channel) with some modifications explained below:

- APs to be assigned channels are chosen randomly.
- Prior flag is always false.
- Check_PB is always true.
- With the purpose of giving the same priority to both bands, (line: 13) they are hereinafter replaced by the following lines:

```
13.         elseif  H(c_s)<H(c_p); Ch(ap_u)← c_s;
14          elseif  H(c_s)=H(c_p); Ch(ap_u)←rand(c_s, c_p );
            ;if the H is the same for both bands the channel is randomly chosen from ISM or PB
14.         elseif  Ch(ap_u)← c_p;
15.         end(12)
16.       end(9)
17.   end(1)
```

5.6.3 Performance Evaluation

This section is divided into two parts, one devoted to non-iterative algorithms, and the other to iterative algorithms.

To analyze the performance of the proposed algorithms, different metrics are introduced in this section, which are detailed as follows: 1) the percentage of feasible assignments consists of the percentage of analyzed scenarios where all the APs have their edges with P below P_{MAX}. 2) the percentage of feasible APs, which represents the percentage of APs with all their edges with P below P_{MAX} and 3) the percentage of APs using primary band. These metrics are evaluated under different conditions of the APs' density and primary spectrum heterogeneity.

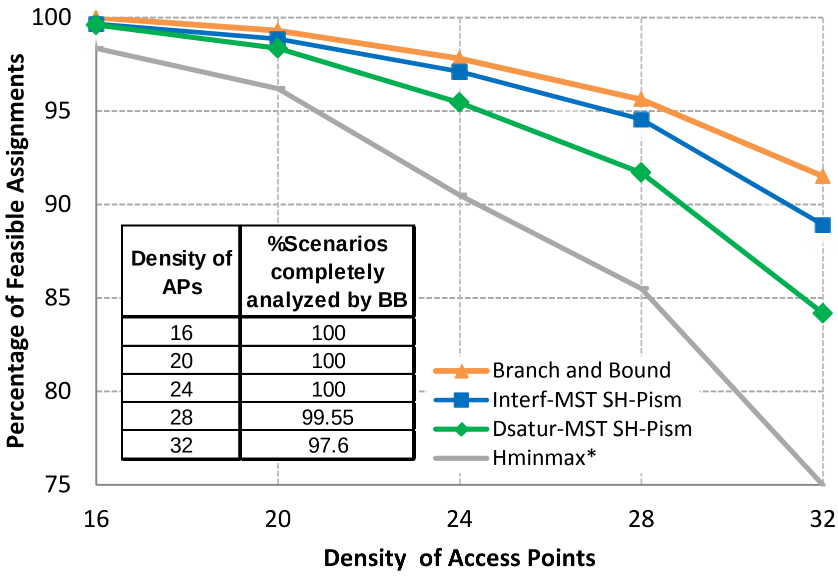
The proposed algorithms are evaluated and their performance is compared to the results obtained from two benchmarks: the former is derived from the Branch and Bound (BB) mechanism which is used to find optimal solutions for the BLP formulation, and the second is obtained by using Hminmax* algorithm, which is a mechanism currently used in WLANs for channel assignment. The algorithms based on MST are referred to as: "X-MST *SH-Pism*", in which X can be either Interf or Dsatur, SH and Pism refer to the fact that the algorithms account for spectrum heterogeneity and prioritization of ISM bands, respectively. Scenario configurations and simulation parameters correspond to those shown in Table 4.1and Table 5.1.

5.6.3.1 Non-Iterative Algorithms

1. *Analysis of Heuristic Solutions Compared to the Optimal Solution*

Results have been obtained from 2000 snapshots and 20 PUs. Figure 5.12 shows the percentage of feasible assignments for several densities of APs deployed in the scenario. From this figure, it can be observed that the results obtained by Interf-MST are closer to the optimal solutions provided by the BB algorithm than the results found by Dsatur-MST and Hminmax*, in that order. So, for instance, for 32 APs, the percentages of feasible assignments obtained by Interf-MST, Dsatur-MST and Hminmax* are around 2, 7 and 17 percentage points below BB.

Figure 5.12 also shows the percentage of scenarios completely analyzed by the BB algorithm; that is to say, scenarios in which the search tree is not limited by configuration settings in the BINTPROG. For instance, for densities of APs from 16 to 24, all scenarios have been analyzed to 100%, so the line mentioned as Branch and Bound in this figure corresponds to optimized solutions plus unfeasible ones brought about by this algorithm. However, for densities greater than or equal to 28 APs, the BB algorithm is not always able to come up with a final solution (e.g. nearly 3% of analyzed snapshots cannot be solved for 32 APs). In these abnormal cases, the solution provided by BB is the last combination under evaluation (that may be neither optimal nor feasible). Note that, in this study the maximum amount of execution time of the algorithm is set to 3600 seconds (i.e. one hour), as a practical configuration to be used, in order to obtain a metric that allows for the identification of the impact of these fields on the performance of the BB algorithm.



Density of APs	%Scenarios completely analyzed by BB
16	100
20	100
24	100
28	99.55
32	97.6

Figure 5.12: Percentage of Feasible Assignments versus Density of APsa, for Branch and Bound, Interf-MST, Dsatur-MST, and Hminmax*

Figure 5.13 shows the usage of the primary band. As seen in the figure, both MST-based algorithms are able to provide similar results to the optimal BB. The percentage of APs using primary band required by Interf-MST is shown to always be lower than that required by Dsatur-MST. For example, Interf-MST finds around 5 percent more feasible assignments than Dsatur-MST and utilizes around 0.4 percentage points less APs operating in primary band, for 32 APs. The figure also shows the use of PB by the Hminmax*. In this case, Interf-MST obtains around 14 percentage points more feasible assignments and requires around 17 percentage points less APs using primary band than Hminmax*.

Notice that, for Hminmax*, the percentage of APs using PB may increase to a value approximately similar to that represented by the number of available primary channels with respect to the total available channels (i.e. ISM+PB), since the APs do not have prioritization of bands being used. For instance, from Figure 4.16, the average percentage of available primary channels for $R_{U,PU}$ =50m is around 50%, so that, considering only non-overlapping channels, on average, each AP only has one (of two possible) available primary channel, consequently the percentage which represents the primary channel with respect to the total channels is around 25% (1 primary channel and 3 ISM channels). Hence, Hminmax* could use up to about 25% of APs in primary band. Non-overlapping channels have been considered because Hminmax * choose the channels that minimize the maximum penalty between APs, this implies that the channels to be assigned to try to have the maximum possible separation between them. However, this calculation is only an approximation.

It is also interesting to note in Figure 5.13 that the performance of BB for higher densities of APs is worse than that of Interf-MST due to the “bad” solutions given by BB when it is not able to conclude its operation.

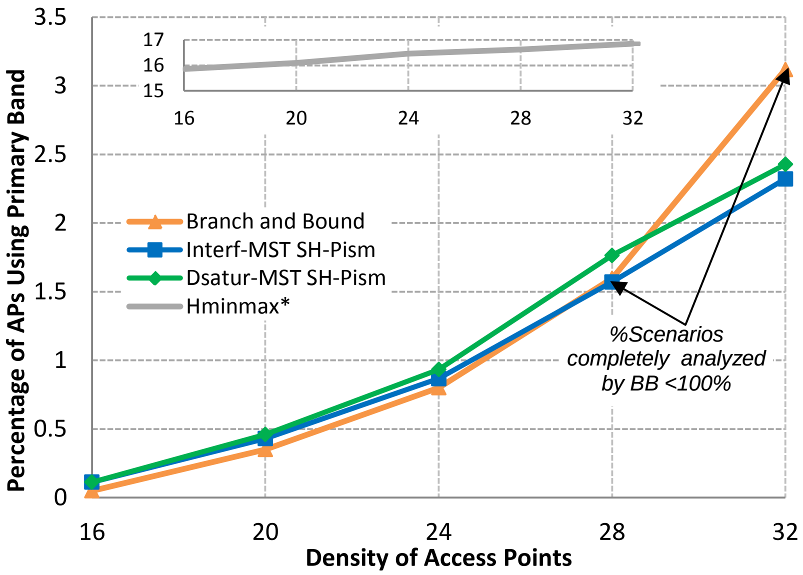


Figure 5.13: Percentage of APs using Primary Band versus Density of APs, for Branch and Bound, Interf-MST, Dsatur-MST and Hminmax*

2. Analysis of Spectrum Heterogeneity and Prioritization Features

The benefits of considering spectrum heterogeneity and prioritization are analyzed next.

Figure 5.14 provides the percentage of feasible assignments for different densities of APs for Inter-MST. When the spectrum heterogeneity is considered, the Interf-MST algorithm achieves more feasible assignments than if it is not considered. For instance, for 36 APs, Interf-MST *SH-Pism* finds around 6 percentage points more than Interf-MST *NoSH-Pism*. Also, when the prioritization of the ISM band is considered, the algorithm finds a few more feasible assignments than if it is not considered, especially when the density of APs in the scenario increases. Therefore, the best solution for finding scenarios in which all APs have their interference penalties below the established threshold is the one that considers the heterogeneity of available primary channels at each AP and the prioritization of the ISM band in the channel assignment process, i.e. Interf-MST-*SH-Pism*. Importantly, the results achieved by any combination of the Interf-MST algorithm are always better than those reached by Hminmax*.

A similar behavior is obtained for the percentage of feasible APs as to different densities of APs within the scenario as shown in Figure 5.15. Because of this, this metric indicates the percentage of APs that meet the stated objective of maintaining their penalties below a certain threshold, although not all APs can achieve this at a given snapshot.

Figure 5.16 shows the percentage of APs using primary band necessary for finding the feasible assignments of Figure 5.14 and feasible APs of Figure 5.15. This figure illustrates, as expected, that when the prioritization of ISM band is considered, the percentage of APs using primary band is significantly less than when it is not considered. For instance, for 36 APs, the difference between the percentage of APs using PB obtained by the algorithms Interf-MST *SH-Pism* and Interf-MST *SH-NoPism* is around 18 percentage points.

Additionally, the amount of feasible assignments obtained by both considerations is similar. Furthermore, the prioritization of ISM band in the channel assignment algorithm allows the APs to be less dependent on the primary channels, and consequently, it makes for a more efficient use of the ISM band.

Similarly, results have also been obtained for the Dsatur-MST in Figure 5.17, Figure 5.18 and Figure 5.19. Particularly, the main difference is that Dsatur-MST *SH-NoPism* is slightly greater than Dsatur-MST *SH-Pism*.

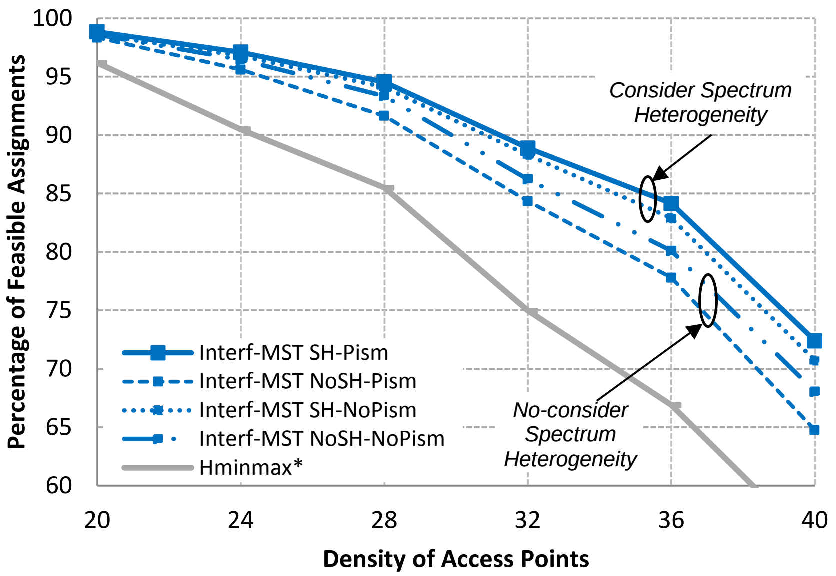


Figure 5.14: Percentage of Feasible Assignments versus Density of Access Points, for variations of the Interf-MST

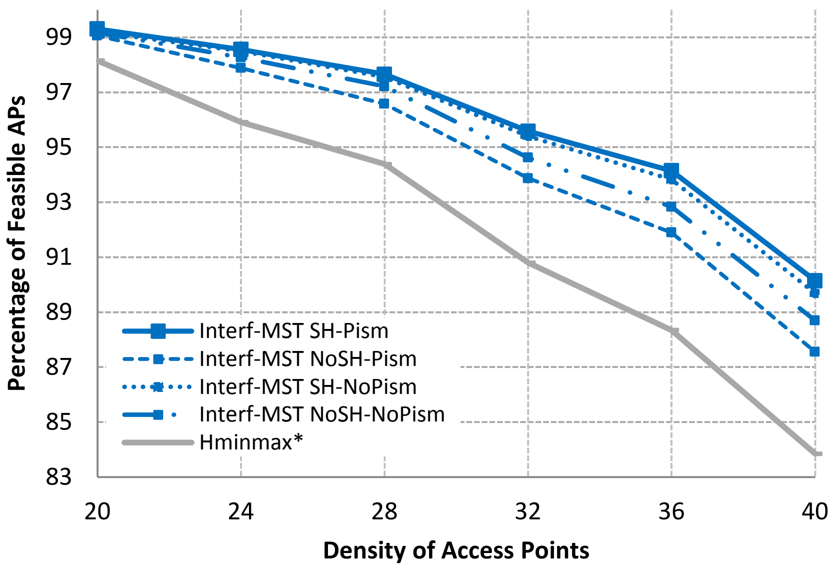


Figure 5.15: Percentage of Feasible APs versus Density of Access Points, for Variations of the Interf-MST

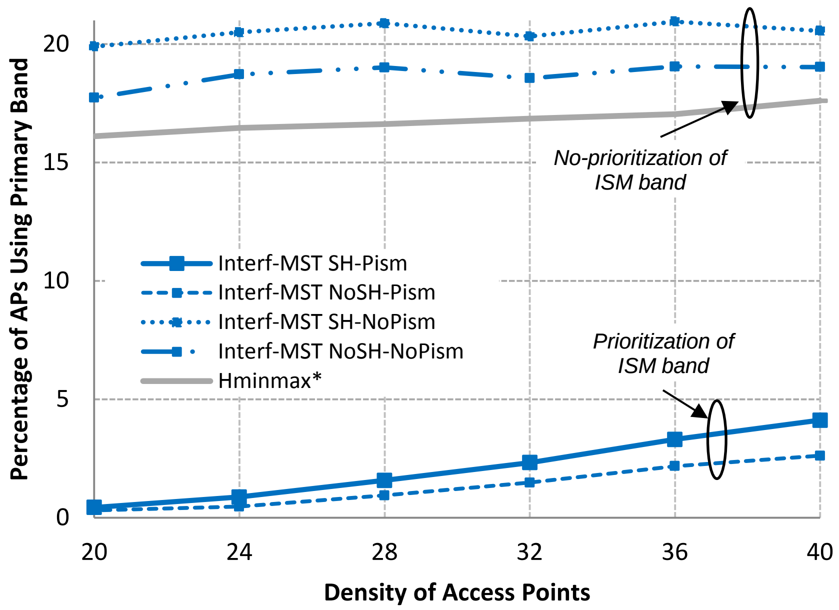


Figure 5.16: Percentage of APs using Primary Band versus Density of Access Points, for Variations of the Interf-MST

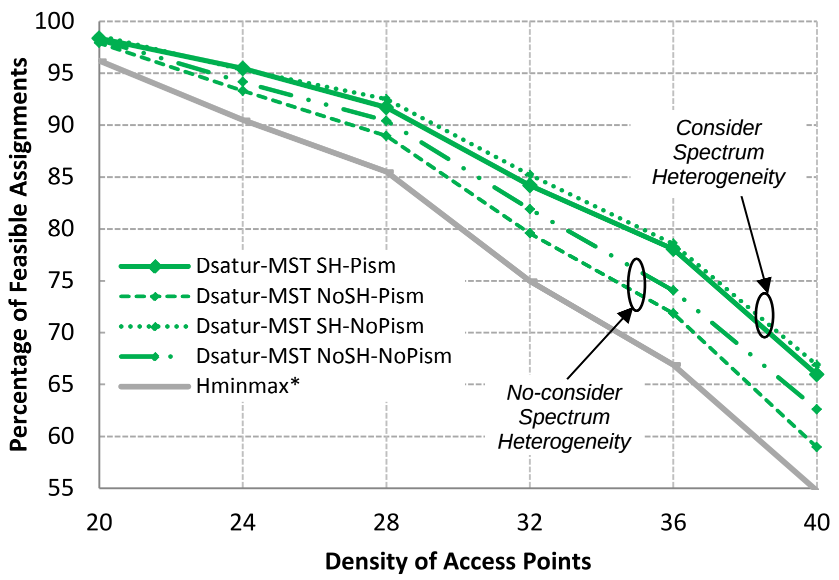


Figure 5.17: Percentage of Feasible Assignments versus Density of Access Points, for Variations of the Dsatur-MST

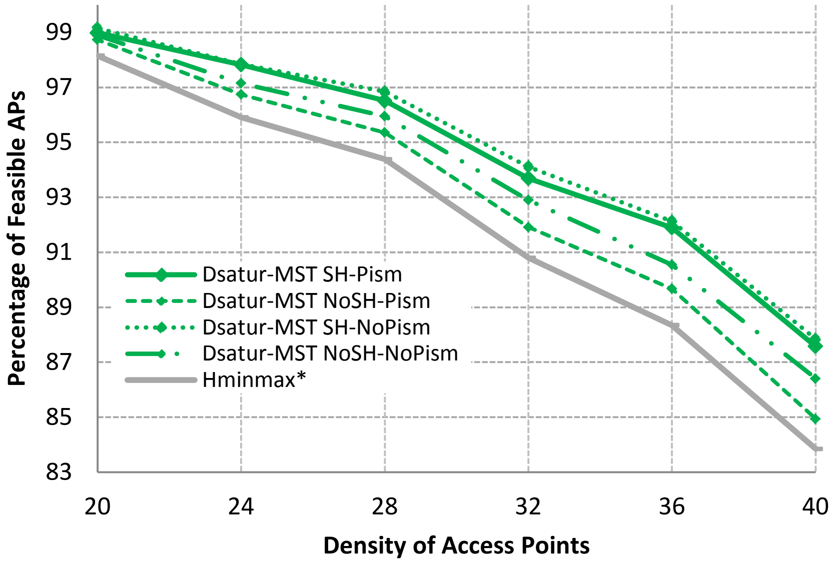


Figure 5.18: Percentage of Feasible APs versus Density of Access Points, for Variations of the Dsatur-MST

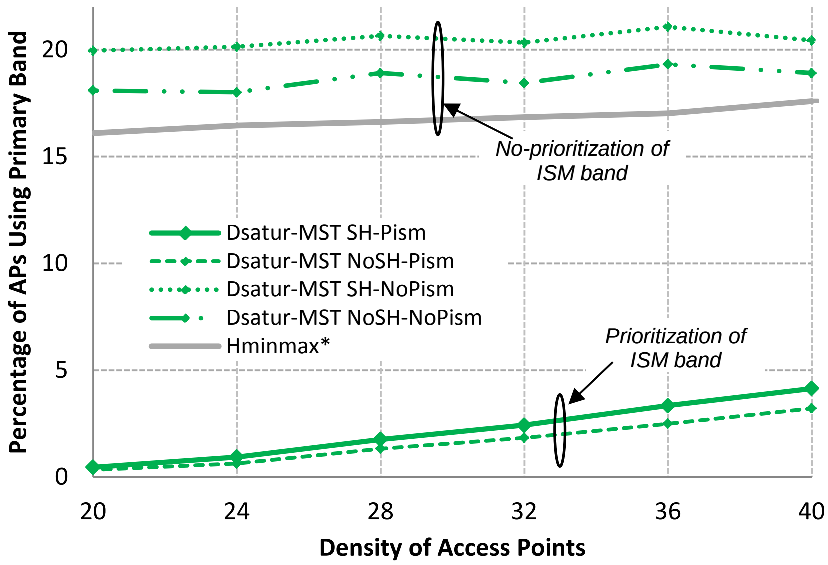


Figure 5.19: Percentage of APs Using Primary Band versus Density of Access Points, for Variations of the Dsatur-MST

3. Analysis of the Spectrum Availability Conditions

Figure 5.20, Figure 5.21 and Figure 5.22 depict the percentage of feasible assignments, feasible APs and the percentage of APs using primary band, respectively, when the spectrum heterogeneity increases (i.e. incrementing density of PUs). The following results were obtained considering 32 APs in the scenario.

These figures illustrate that Interf-MST *SH-Pism* makes more efficient use of additional spectrum than Dsatur-MST *SH-Pism* and Hminmax*, because it finds more feasible scenarios and exposes the APs to much less possible changes in the primary band. For instance, when no PUs are admitted in the scenario, Interf-MST *SH-Pism* requires approximately the same percentage of APs using primary band as Dsatur-MST *SH-Pism* for a density of 8 PUs and provides around 6 percentage points and 2.5 percentage points more feasible assignments and feasible APs, respectively.

So, too, the inefficiency of the Hminmax* algorithm is proven, as it always uses the primary band much more than the proposed algorithms intended, and achieves the least amount of feasible assignments and feasible APs.

It is also observed that, in increasing the number of PUs, the algorithms tend to decrease the amount of APs used in the primary band, although this value is similar for both algorithms. However, the feasibility results obtained by Interf-MST *SH-Pism* still remain better than those obtained by other algorithms. For instance, for 28 PUs, Interf-MST *SH-Pism* finds around 2.13 percentage points of feasible APs and 5 percentage points more feasible assignments than Dsatur-MST *SH-Pism* by using 0.14 percentage points less APs in the primary band (i.e. similar amount of APs in PB for both algorithms).

Notice that, Hminmax* has around 40% of the APs using the PB when no PUs are deployed in the scenario. This fact is related to the percentage of available primary channels (i.e. 2 from PB) over the total of available channels (i.e. 2 from PB + 3 from ISM), this is around 40%.

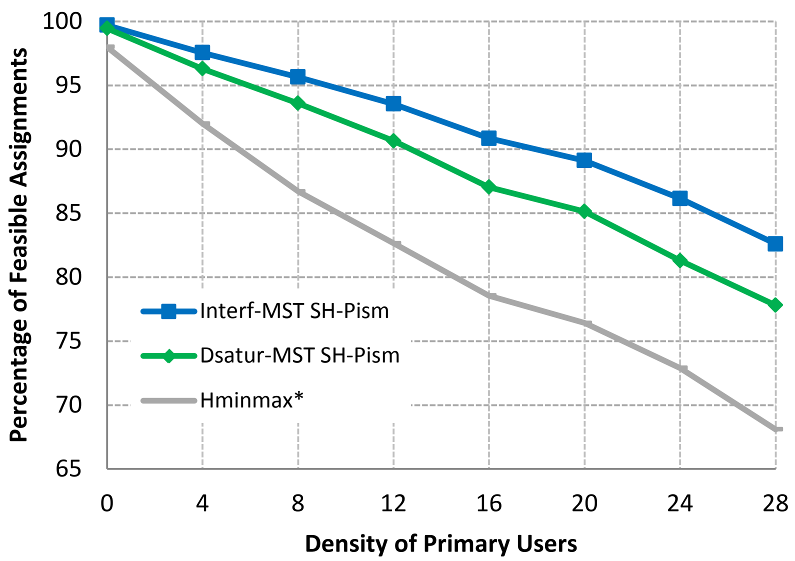


Figure 5.20: Percentage of Feasible Assignments versus Density of Primary Users, for Non-Iterative Algorithms

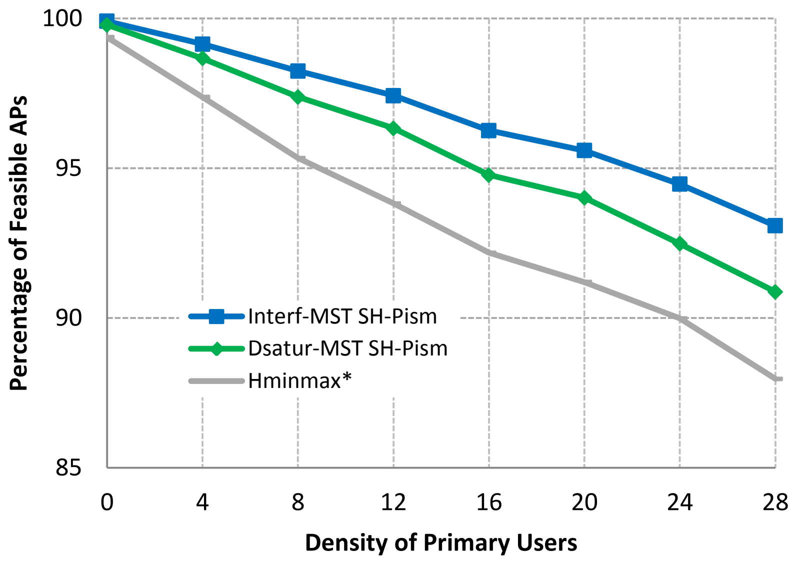


Figure 5.21: Percentage of Feasible APs versus Density of Primary Users, for Non-Iterative Algorithms

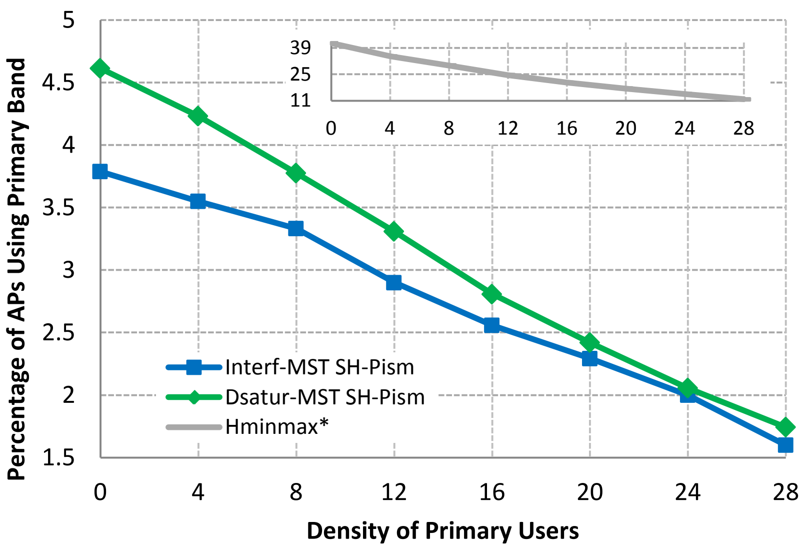


Figure 5.22: Percentage of APs Using Primary Band versus Density of Primary Users, for Non-Iterative Algorithms

5.6.3.2 Iterative Algorithms

In this section, the performance evaluation of three iterative algorithms is analyzed. In particular, the CSA algorithm, an iterative version of the algorithms Interf-MST and Hminmax* are evaluated and referred to as Interf-MST-ite and Hminmax*-ite, respectively.

The implementation of Interf-MST-ite consists of an iterative version of the Interf-MST SH-Pism algorithm, because this one obtained better results than Dsatur-MST. On the other hand, Hminmax*-ite is used as a benchmark.

Table 5.1 shows the configuration parameters utilized by the iterative algorithms. These have been obtained in some cases after performing exhaustive tests.

Table 5.2: Configuration Parameters

	Parameters	**Value**
Convergence Parameters	Number of previous variations, *r*	10
	Minimum value of variation allowed, *Q*	0.005
CSA Parameters	Midpoint at the Utility Function, *q*	0.5
	Slope of the Utility Function, *s*	10
	Number maximum of iterations, n_{max}	500
	Minimum temperature, T_{min}	$1x10^{-5}$
	Initial temperature, T_0	10
	Cooling Rate, *CR*	0.8
	Constant used by CSA, ε	$1x10^{-1}$

1. Tuning CSA and Convergence Conditions

Figure 5.23 illustrates the number of iterations that CSA requires before finding the convergence state for various values of cooling rate, *CR*. From this figure, it can be appreciated that the number of iterations is proportional to the *CR* value. This is because, for high values of *CR*, the temperature decreases more slowly than for low values; consequently, the probabilities (i.e., line: 8, 12 from Figure 5.11) of the CSA algorithm decrease. This fact causes the APs to be exposed to more channel reassignments so that the algorithm could perform more iterations to find better channels and not stay with a local optimum solution.

However, this cost on the number of iterations provides a greater benefit in obtaining more feasible APs and in less use of the primary band by APs, as illustrated in Figure 5.24 and Figure 5.25, respectively. For instance, for 48 APs, if the algorithm is configured *CR*=0.8, it requires running around 6 iterations more than for *CR*=0.1, but obtains close to 2.5 percentage points more feasible APs and 1.5 percentage points less APs using the primary band. Therefore, *CR*=0.8 is the value chosen for the simulation of the CSA algorithm. For *CR* values higher than 0.8 that were tested, the cooling is much slower, and it is necessary to adjust the other parameters.

After studying the parameters of the algorithm, the results obtained, for *BP* values from 0 up to 1, the percentage of feasible access points obtained is up to 0.5 percentage points higher than that obtained by *BP*=0. In the same way, the number of APs using the primary band increases by up to around 16 percentage points. Hence, in order to obtain a good percentage of feasible APs and a reasonable use of the primary band, the value chosen for *BP* is 0. Also, for all evaluations of CSA, initial channel assignment is obtained by assigning the same channel to all Aps, in this case, channel 1.

Note that any configuration of *CR* in the CSA algorithm provides better results than Hminmax*-ite.

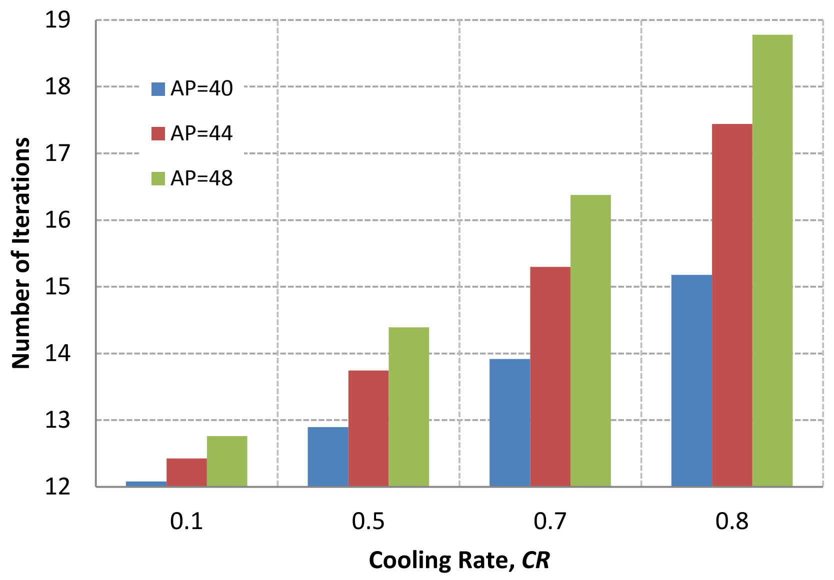


Figure 5.23: Number of Iterations versus Cooling Rate, for CSA

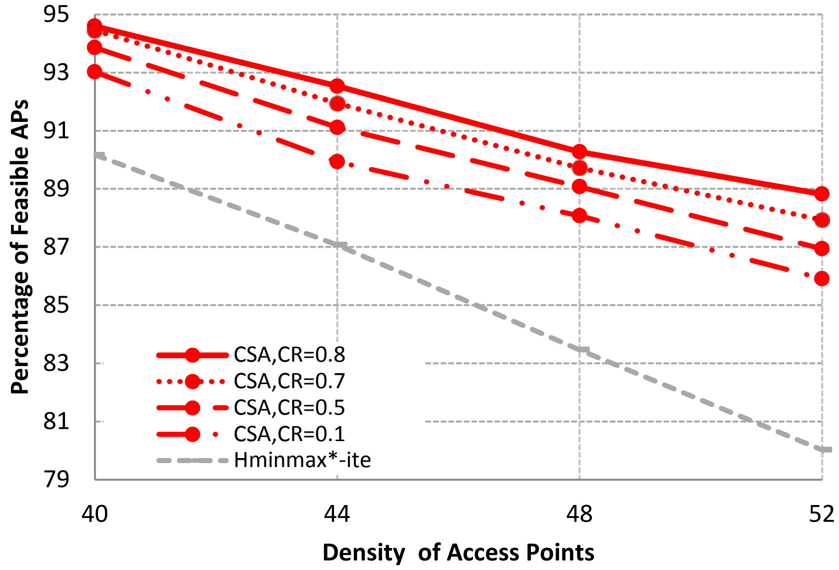


Figure 5.24: Percentage of Feasible APs versus Density of Access Points, for Different Values of CR at the CSA Algorithm

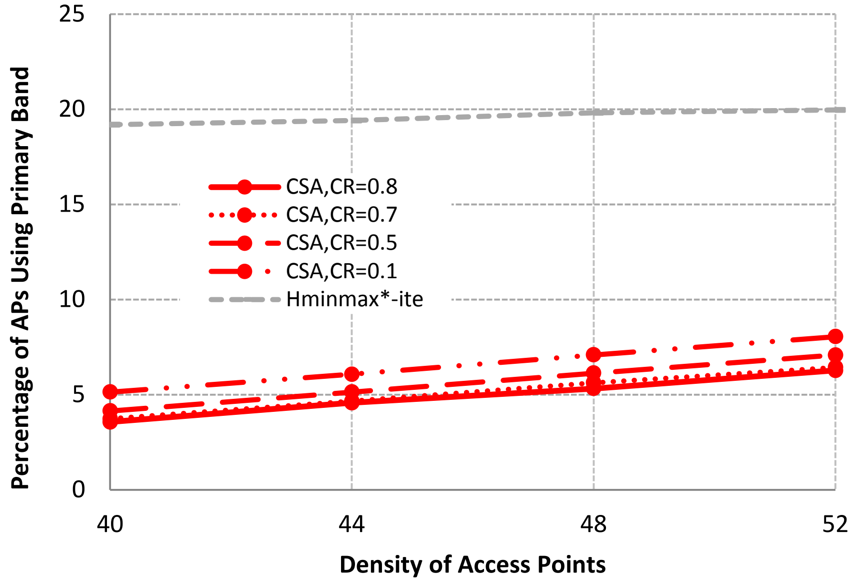


Figure 5.25: Percentage of APs using Primary Band versus Density of Access Points, for Different Values of CR at the CSA Algorithm

To achieve the convergence state, each algorithm needs a different number of iterations *n*, as shown in Figure 5.26. From this figure, before converging, the CSA algorithm requires a higher number of iterations to be run than the other algorithms when the complexity of the scenario is increased (i.e. more APs deployed in the scenario). This is because CSA is a non-greedy algorithm, since it allows the APs to be assigned channels at each iteration that do not increase their penalties. Moreover, Interf-MST-ite and Hminmax*-ite have only allowed assigning channels to increase their penalties so that the criterion used by these two algorithms limits the readjustment of channels at each iteration.

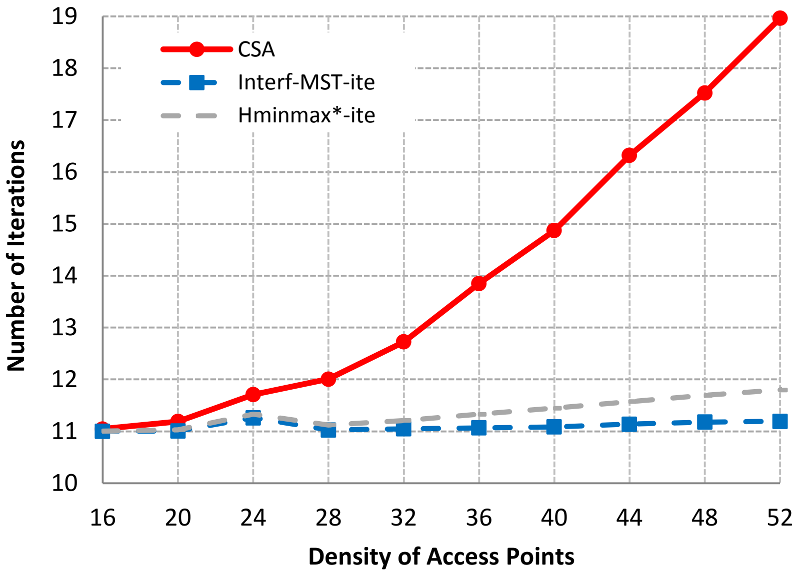


Figure 5.26: Number of Iterations versus Density of APs, for CSA, Interf-MST and Hminmax

2. *Performance Assessment*

From Figure 5.27, Figure 5.28 and Figure 5.29, it can be seen that the performance of the iterative algorithms is better than the one obtained from the non-iterative versions and shown in Figure 5.14, Figure 5.15 and Figure 5.16, respectively. So, for instance, for 40 APs, Interf-MST-ite finds around 3 percentage points more feasible assignments, 2 percentage points more feasible APs and 0.5 percent less APs using primary band than its non-iterative version.

A significant increase in the performance of the Hminmax* is also observed. This is because the penalties at each AP in the initial assignment are so high that in the following reassignments, the algorithm has margin to improve its performance. This fact is reflected in the number of iterations performed by Hminmax*-ite, which is slightly greater than those of Interf-MST-ite. However, the Interf-MST-ite always yields a better performance than Hminmax*-ite.

From these figures, the performance obtained by CSA is also appreciated. This algorithm finds better results than Interf-MST-ite and Hminmax*-ite. This is mainly due to the channel reassignment criterion applied by this algorithm channel, which, even while doing a higher number of iterations, is able to achieve better performance results. For example, for 60 APs, CSA finds around 6.34 percentage points and 11 percentage points more feasible APs and requires about 2 percentage points and 12 percentage points less APs in primary band than Interf-MST-ite and Hminmax*-ite, respectively.

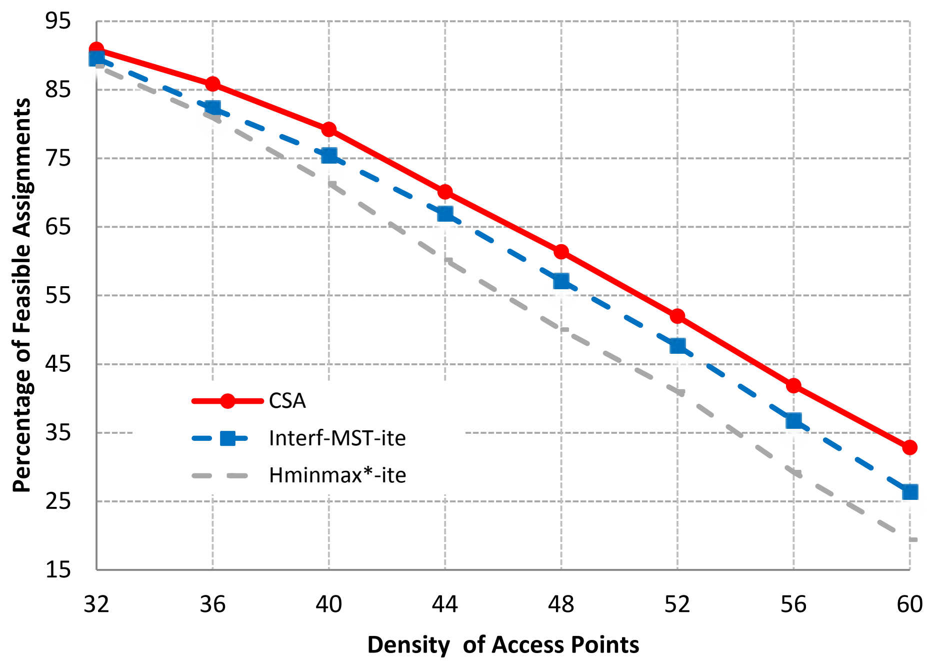


Figure 5.27: Percentage of Assignments versus Density of Access Points, for Iterative Algorithms

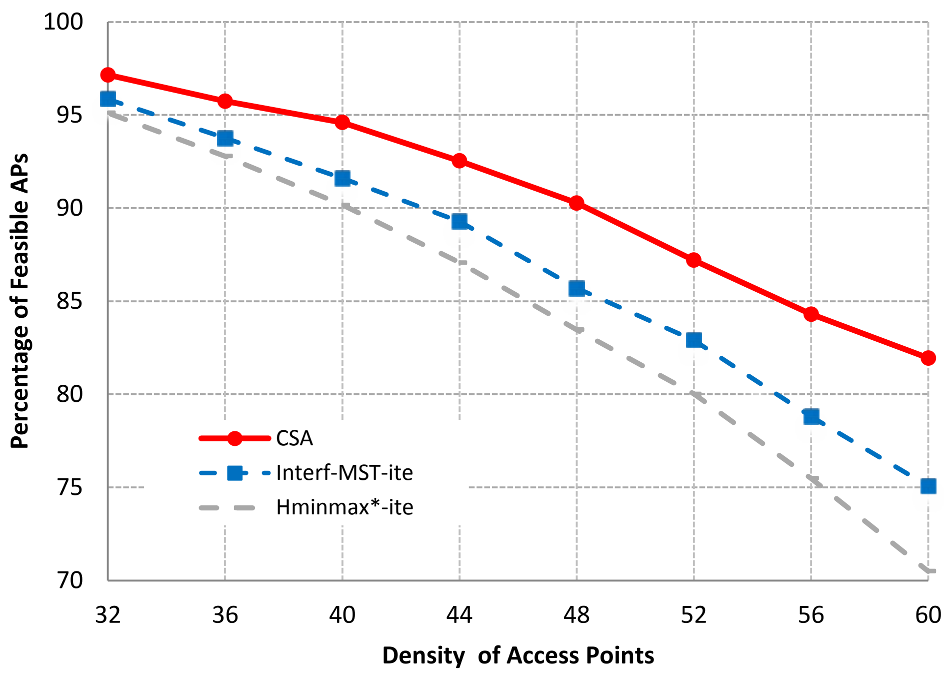


Figure 5.28: Percentage Feasible APs versus Density of Access Points, for Iterative Algorithms

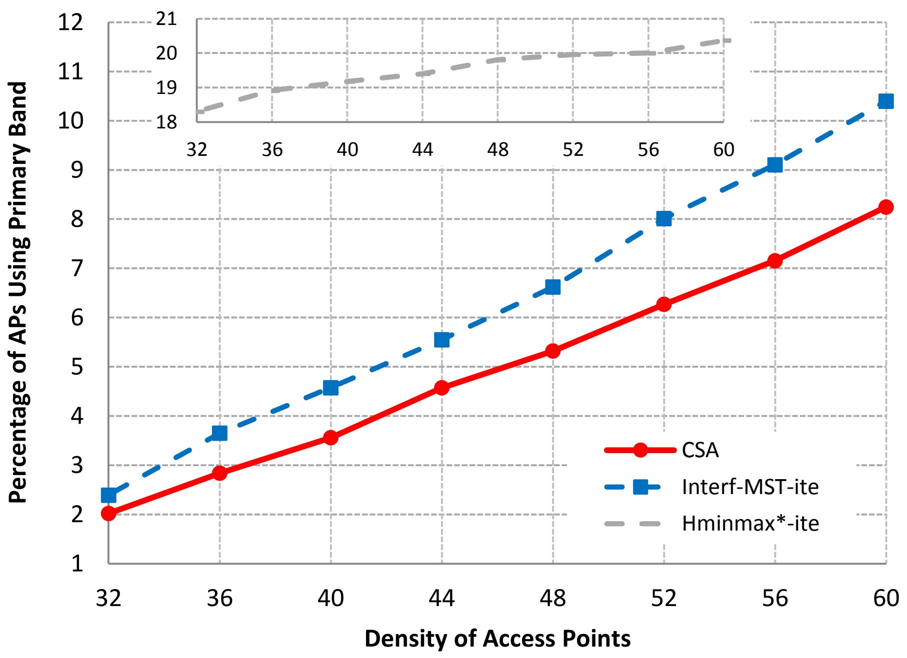


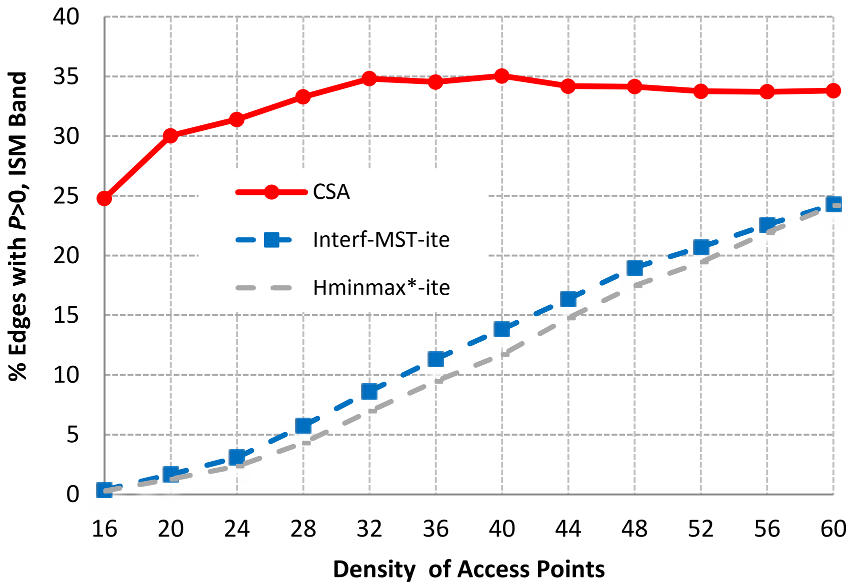
Figure 5.29: Percentage APs Using Primary Band versus Density of Access Points, for Iterative Algorithms

In the following figures, an analysis of the algorithms' performance is carried out in terms of the penalties in the network scenario, considering ISM and primary bands separately and 20 PUs in the scenario.

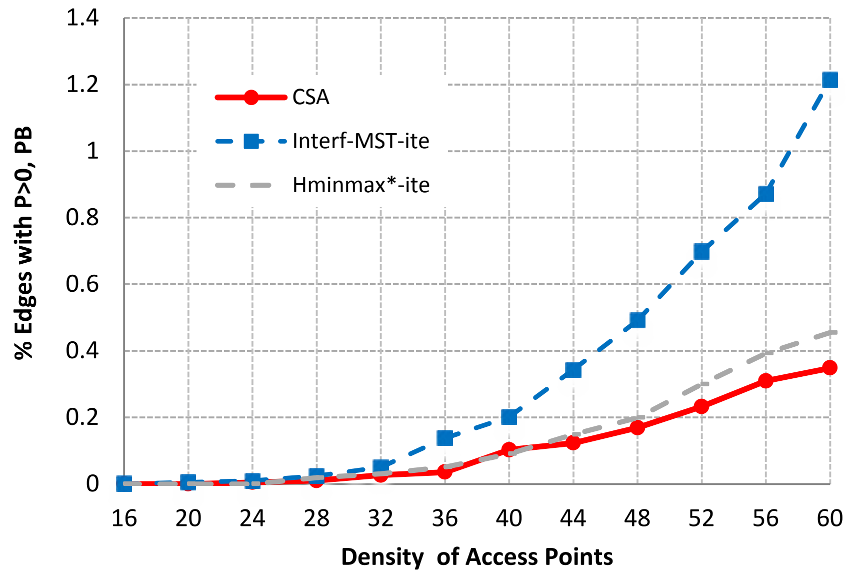
Figure 5.30 illustrates the percentage of edges with a penalty greater than zero for different densities of APs. Figure 5.30a shows that the ISM band concentrates a higher percentage of edges with a penalty greater than zero than those in the primary band, as shown in Figure 5.30b. So, for instance, for 44 APs, CSA produces around 34% of edges that have some penalty in ISM band and 0.12% in PB.

CSA generates a lot more edges with $P > 0$ in ISM band than the other algorithms, although in the primary band, the opposite behavior is observed. Thus, CSA tries to balance the penalty between the different edges in the ISM band, in order to use the primary band as little as possible.

Also, it can be appreciated that the Interf-MST-ite obtains a percentage of edges with $P>0$ less than CSA in ISM, while, for primary band, this percentage is greater than the other algorithms. This behavior is a consequence of the fact that the W defined for building the MST depends on the λ and P between APs. Because of that, the APs with a lower availability of primary channels are assigned first and, with perference to the ISM band channels rather than the primary channels. This fact causes the APs with a greater availability of primary channels to find high penalties between APs in the ISM and forces them to utilize primary channels. However, as shown in Figure 5.30b the percentage of edges with $P > 0$ in PB for Interf-MST is higher than the other algorithms, but this value is very low (e.g. around 0.1% for 44 APs) in comparison to the ISM band.



a.



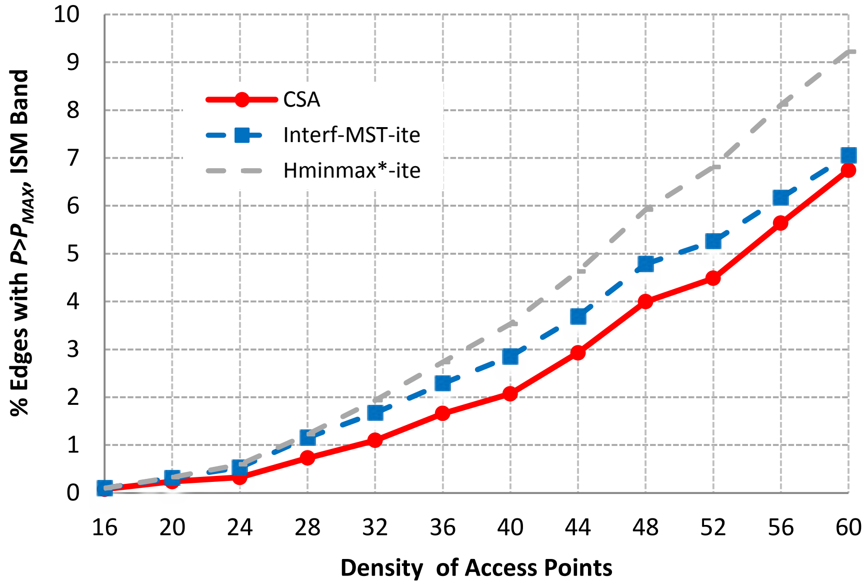
b.

Figure 5.30: Percentage of Edges with Penalty Greater than Zero in the Scenario versus Density of APs, for Iterative Algorithms

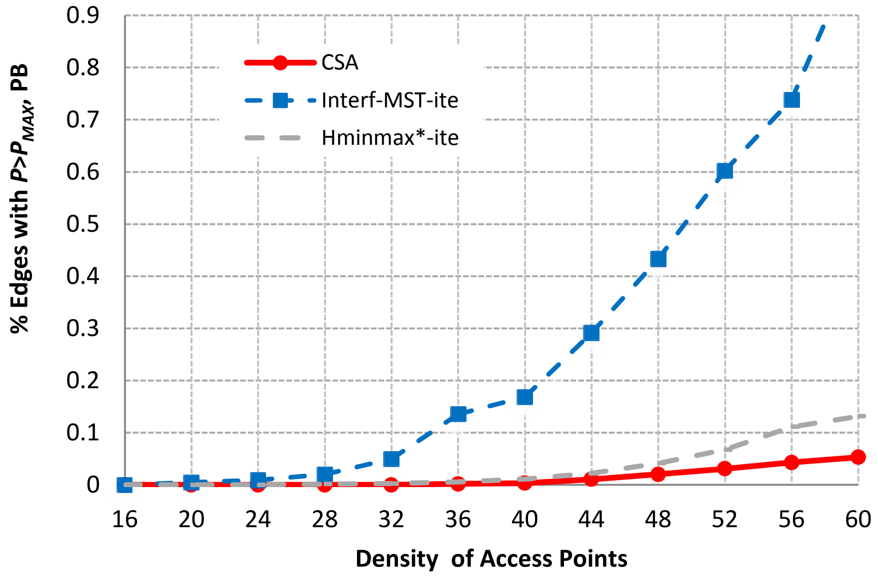
Figure 5.31 depicts the percentage of edges with $P>P_{MAX}$ for ISM band and primary band. The percentage for ISM band illustrated in Figure 5.31a is much higher than the one obtained in primary band, shown in Figure 5.31b.

Figure 5.31a indicates that CSA obtains the least percentage of edges with $P>P_{MAX}$ in ISM, followed by Interf-MST and Hminmax*, in that order. This fact confirms the obtained feasibility results shown in Figure 5.28, because the algorithms with a lower percentage of edges with $P>P_{MAX}$ obtain a higher percentage of feasible APs.

Therefore, the APs operating in the ISM band are responsible for the decrease of the feasibility of the algorithms, since the percentage of edges with $P>P_{MAX}$ in the ISM is much greater than in the primary band, so that the percentage of edges with $P>P_{MAX}$ in the primary band has little effect on the feasibility of the algorithms. So, for example, for 60 APs, CSA has around 7% of edges with $P>P_{MAX}$ in ISM band while, in PB, it only has 0.053%. In this way, it is evident that the loss of feasibility is caused by $P>P_{MAX}$ in the ISM band.



a.

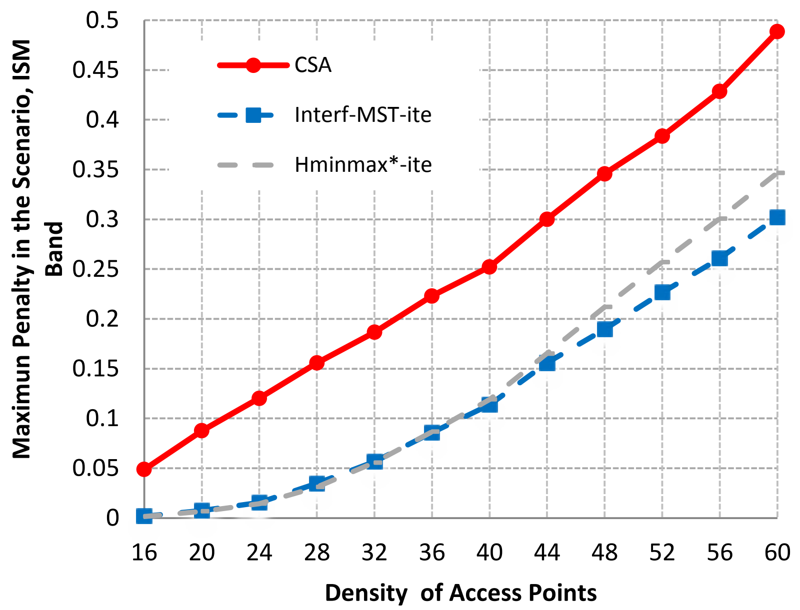


b.

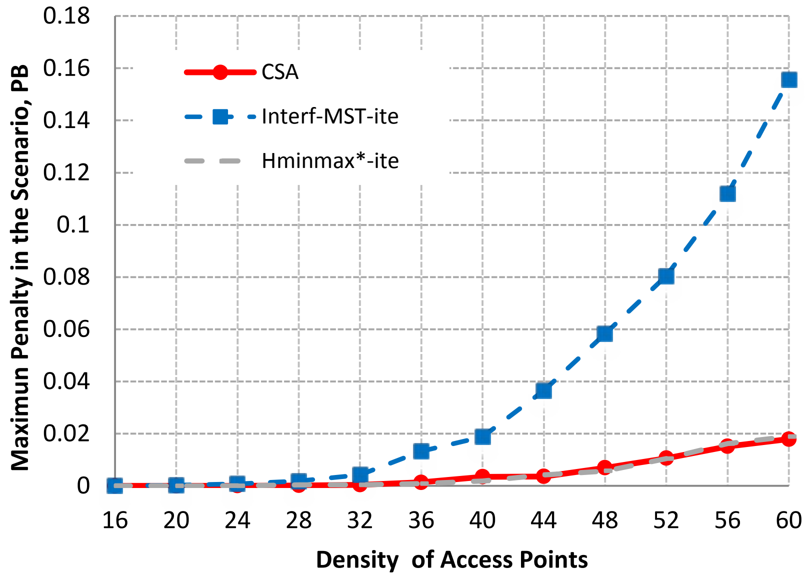
Figure 5.31: Percentage of Edges with Penalty Greater than the Penalty Maximum in the Scenario versus Density of APs, for Iterative Algorithms

As seen in Figure 5.32a, the maximum penalty from all the edges in the scenario in the ISM band is obtained by CSA. This fact does not represent a lesser number of feasible APs when CSA is compared to the other algorithm, because, as depicted in Figure 5.31a, the percentage of edges with $P>P_{MAX}$ for CSA is the lowest. Notice that this behavior of CSA is related to the results shown in Figure 5.30a, where CSA has the highest percentage of edges with $P> 0$.

In the primary band, the Interf-MST obtains the highest maximum penalty from all the edges, as exposed in Figure 5.32b. However, these values are always below the maximum penalty and have little influence in the obtaining of feasible APs.



a.

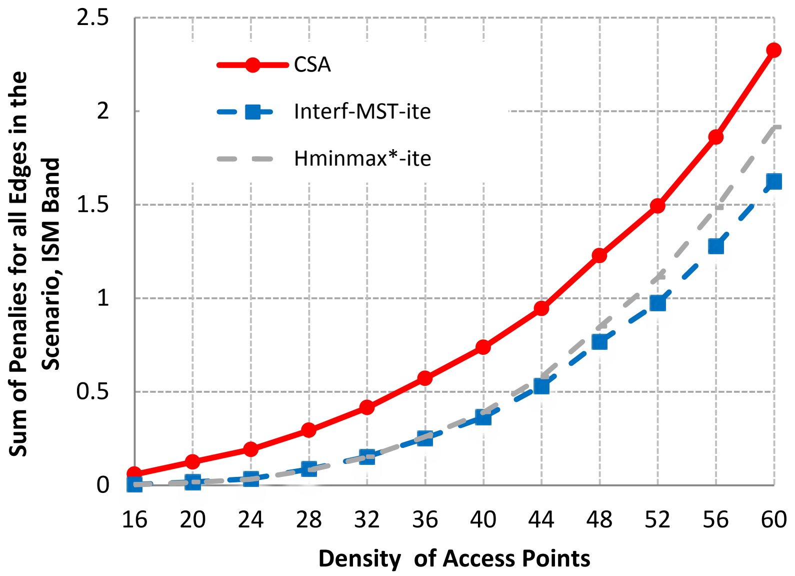


b.

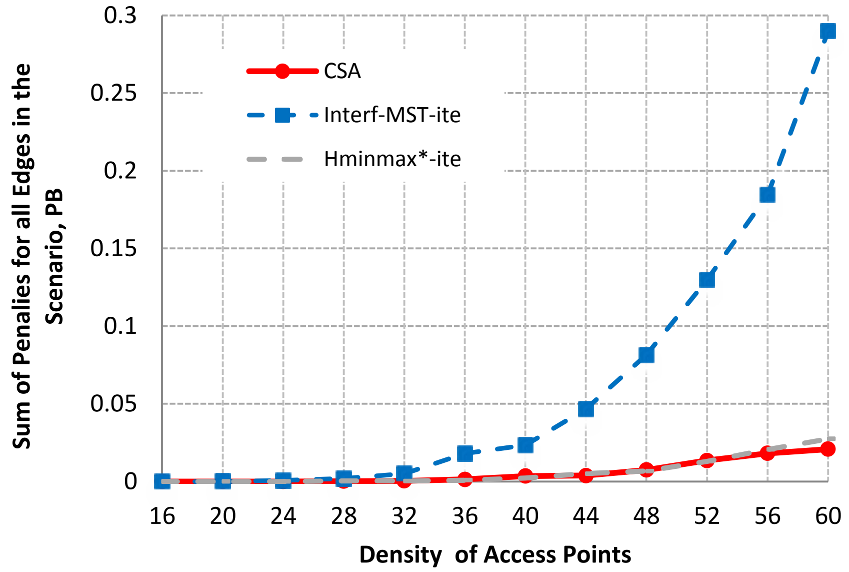
Figure 5.32: Maximum Penalty in the Scenario versus Density of APs, for Iterative Algorithms

Figure 5.33 exposes the sum of penalties of edges in the entire scenario for ISM and primary bands with respect to different numbers of APs. Figure 5.33a allows us to appreciate that, for the CSA algorithm, the sum of penalties for all the edges in the scenario in the ISM band is greater than the other algorithms. This fact is caused by the presence of the highest number of edges with a penalty greater than zero being generated by this algorithm, as shown in Figure 5.30a.

From Figure 5.33b, it can be concluded that Interf-MST-ite obtains less APs using the primary band, but that those APs have a higher sum of penalties between them; whereas Hminmax*-ite operates with the highest number of APs in the primary band, but with a low penalty between APs.



a.



b.

Figure 5.33: Sum of Penalties for all Edges in the Scenario versus Density of APs, for Iterative Algorithms

3. *Spectrum Availability in the Network Scenario*

In Figure 5.34 and Figure 5.35, the impact on the performance of iterative algorithms caused by the variations of primary users in the network scenario is analyzed. It is noted that the algorithms improve their performance in that the non-iterative algorithms gain feasibility and reduce the primary band usage. Such a case is more remarkable in the Hminmax*-ite than in Interf-MST-ite, because it has done more iterations to reassign channels. Results have been obtained using 32 APs in the scenario.

It also observed that CSA has better performance than the other algorithms, in that it obtains more feasible assignments and feasible APs with less primary band usage than the others. CSA is more stable than the other algorithms when it comes to changes in the spectrum heterogeneity; this can be observed in the percentage of feasible assignments obtained by CSA, which decreases more slowly than with the other algorithms.

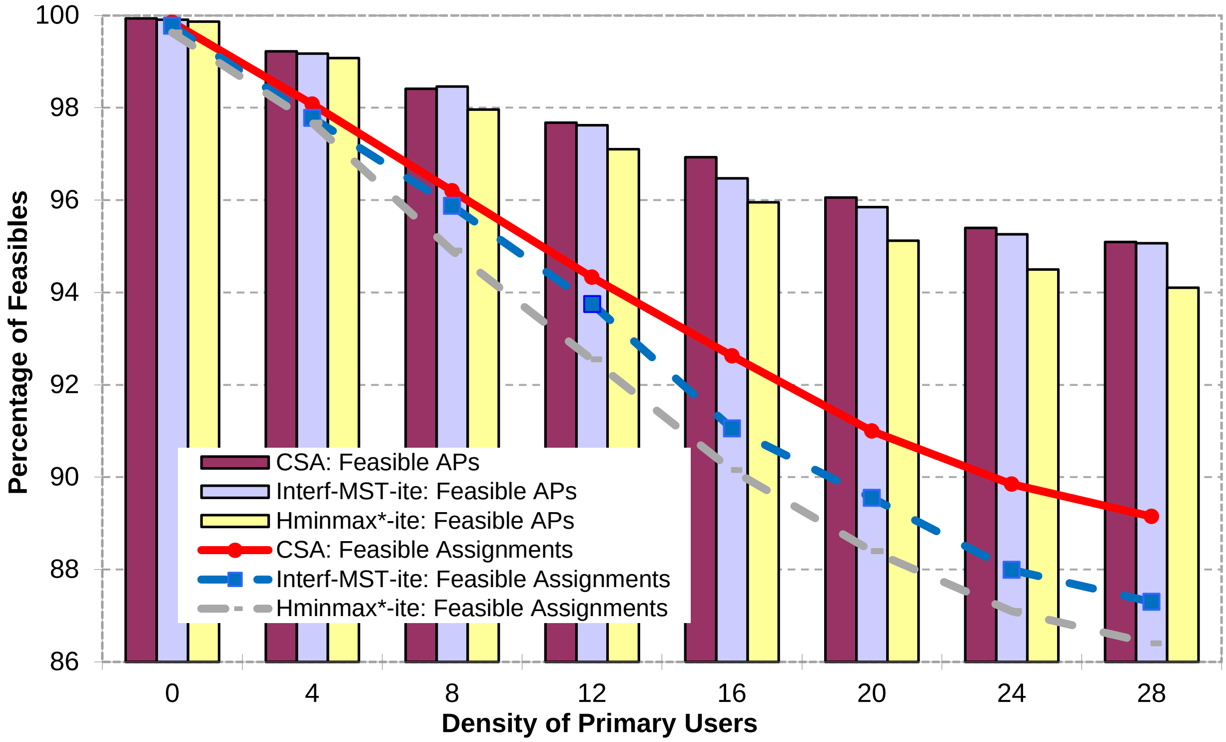


Figure 5.34: Both Percentage of Feasible Assignments and Percentage of Feasible Access Points versus Density of Primary Users, for Iterative Algorithms

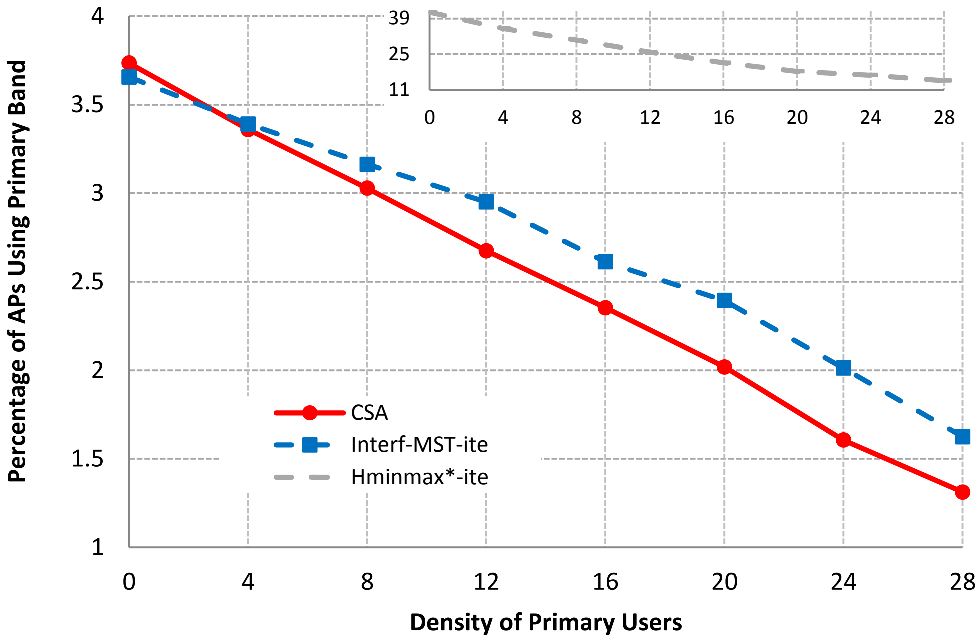


Figure 5.35: Percentage Feasible APs versus Density of Primary Users, for Iterative Algorithms

4. *Error Margin Analysis*

Figure 5.36 provides the error margin of the percentage of feasible APs for each algorithm, considering sets of 100, 1000, and 2000 snapshots, and 10 samples per set of snapshots. From this figure, it can be observed that the obtained error margin for sets of 2000 snapshots is always less than 1 percentage point. On the other hand, for sets of 100 snapshots, the achieved error margin is about 2 percentage points. Hence, the simulations in this work were performed for sets of 2000 snapshots because the obtained error margin is the least.

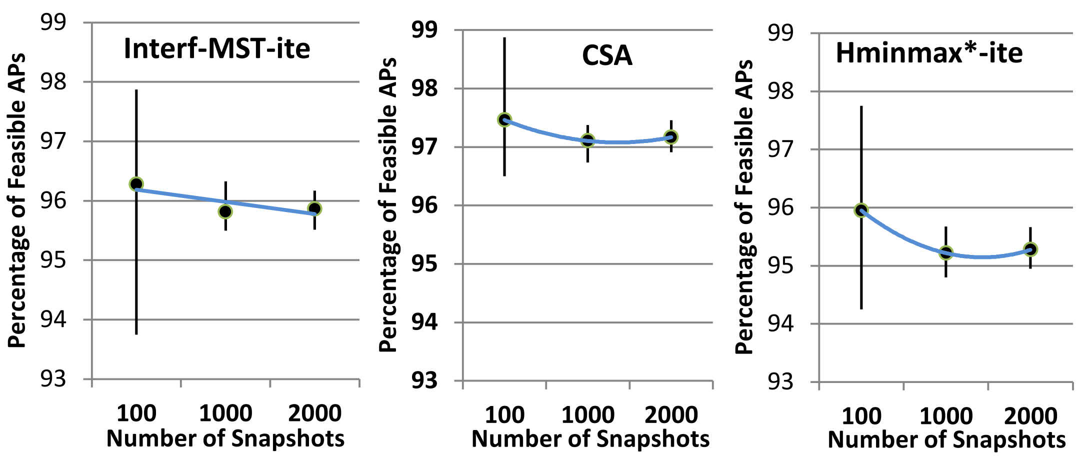


Figure 5.36: Error Margin of the Percentage Feasible APs for Different Number of Snapshots, considering 10 samples per number de Snapshot, 32 APs and 20 PUs

5.7 Distributed Computing Solution

In this section, a distributed channel assignment mechanism that tries to meet the objective described in Section 5.2 is developed by means of a heuristic algorithm based on distributed computing techniques. The algorithm is executed by each AP in a distributed manner, and it is carried out based only on local information, i.e. no information exchange takes place between neighboring APs.

5.7.1 Distributed Simulated Annealing

In this section, a distributed channel assignment mechanism is developed by means of a heuristic algorithm based on simulated annealing techniques. This proposal is a distributed adaptation of the CSA algorithm that was introduced above for channel assignment in a centralized approach.

It is assumed that APs only have local information. However, each AP, with the purpose of obtaining local information, could scan each channel in order to discover the beacons transmitted by its neighbors. Since each beacon is individual for each AP and contains information such as the type of BSS, SSID, operating channel, the AP can capture certain key information about its environment from each beacon. Figure 5.37 depicts a graph with the proposed scenario.

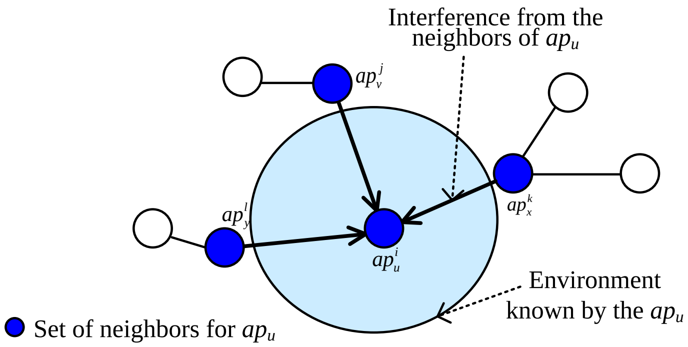


Figure 5.37: APs Deployment on the Proposed Scenario

The objective of the channel assignment problem is then set out to maximize the utility function at each AP (i.e. 5.12). Hence, the channel assignment problem for each AP can be formulated simply as:

$$\text{maximize } \left(U^i_{ap_u}\right) \quad (5.16)$$

Subject to: ap_u only uses one channel at a time

Algorithm Description

The algorithm is executed locally at each AP and allows each one to select its operation channel, either from an ISM band or a primary band. The algorithm is made using the simulated annealing technique that uses a stochastic approach to direct the search of a channel assignment and is targeted to maximize the utility function of the AP. This one is referred to as distributed simulated annealing (DSA). DSA could be activated by variations of some external parameter, such as the availability of primary channels, the increase of penalties at any edge, etc. The local search method is shown in Figure 5.38 .

Notation of Figure 5.38 for the utility function has been simplified because, as the algorithm is executed at each AP, the utility of that particular AP is just expressed as $U_{ap_u}^{i} = u(i)$.

The algorithm works as follows: At each access point, the algorithm starts if any change in the network environment of the AP is detected (e.g., number of neighbors, number of available primary channels, etc).

DSA parameters such as the initial temperature T_0, cooling rate *CR*, the predefined constant $\in$, the minimum cooling temperature T_{min}, and the maximum number of iterations $n_{d\text{-}max}$ are initially configured. Notice that $n_{d\text{-}max}$ corresponds to the maximum number of iterations that each AP can execute independently.

The algorithm computes an initial channel, *i*, that is assigned to the AP as the current operation channel (line: 1). In particular, channel 1 is assigned.

Stopping criterion are the same as those used by CSA, except that an iteration at DSA corresponds to a possible reassignment of a channel to a certain AP (line: 2), CSA instead takes into account possible reassignments for all APs.

The algorithm is executed iteratively. Thereby, a new channel, *j*, is obtained as a candidate channel to be assigned to the AP at each iteration (line: 3). For computing the candidate channel, the same mechanism is used as the one defined in section 5.6.2 for CSA by replacing $TU_{ap_u}^{i}$ by $u(i)$.

The decision to keep the current channel, *i*, or assign the candidate channel, *j*, depends on a comparison between utilities obtained by those channels. Therefore, if $u(i)$ is the utility obtained with the current channel and $u(j)$ with the candidate channel, then the candidate channel is assigned to the AP if the utility is incremented, i.e. $\delta = u(i)-u(j)<0$ (line: 4-6). If the candidate channel decreases the utility, it will be accepted with the probability depending on the change in utility δ and the current temperature *T*, $\Pr[\delta,T]=e^{-\delta/T}$ (line: 7-9). On the other hand, if the candidate channel provides the same utility as the current channel, it will be accepted with the probability depending on the predefined constant, $\in$ and *T*, $\Pr[\in,T]=e^{-\in/T}$ (line: 11-13). Otherwise, the operation channel does not change.

T values are updated at each iteration (line: 16) and gradually decrease so that the probability of accepting a new channel that does not improve the utility also decreases. For this algorithm, these parameters are used as stopping criterions.

Algorithm: DSA

Data: Temperature T_0, CR, $\in$, V, E, N, $n_{d\text{-}max}$, T_{min}
Result: max U

1. Compute initial channels *i*
2. **while** *stopping criterion* is not reached
; Verify if any $n_{d\text{-}max}$ or T_{min} are achieved
3. Obtain new channel *j*
;*j* is a candidate channel
4. Compute $\delta = u(i) - u(j)$
5. **if** $\delta < 0$ **then**
6. $i = j$;
7. **elseif** $\delta > 0$ then
8. **if** *random*[0,1] < $e^{(-\delta/T)}$ **then**
9. $i = j$;
10. **end**(8)
11. **elseif** $\delta = 0$ then
12. **if** *random*[0,1] < $e^{(-\in/T)}$ **then**
13. $i = j$;
14. **end**(12)
15. **end**(5)
16. Update $T = CR \cdot T$ and *number of iterations* (n_d)
17. **end**(2)

Figure 5.38: Pseudocode of the DSA Algorithm

5.7.2 Performance Evaluation

In this section, a performance analysis of the proposed algorithm is carried out under different conditions of the APs' density and primary spectrum heterogeneity. The configuration parameters are the same as those used by CSA. DSA is evaluated and compared with Hminmax*-ite, which is a distributed mechanism currently used by WLAN. Scenario configurations and simulation parameters correspond to those shown in Table 4.1 and Table 5.1.

1. <u>Convergence Analysis</u>

The convergence criterion is the same as the one defined for iterative algorithms so that the algorithm is executed at each AP until the percentage of feasible APs deployed in the scenario is stabilized. For these simulations, 20 PUs in the scenario have been considered.

Hence, the number of iterations executed at each AP (n_d) can be different from the number of iterations needed for converging (n). Because of this, any AP can achieve the stopping criterion independently of the convergence criterion, which considers the stability of feasible APs in the entire scenario and vice versa.

In order to analyze the performance of the distributed algorithms in the entire scenario, Figure 5.39 shows the number of iterations (n) needed for finding the convergence criterion. The behavior is similar to that obtained for CSA; that is, DSA executes a higher number of iterations than Hminmax*, given that this one has a more flexible criterion for assigning channels to the APs.

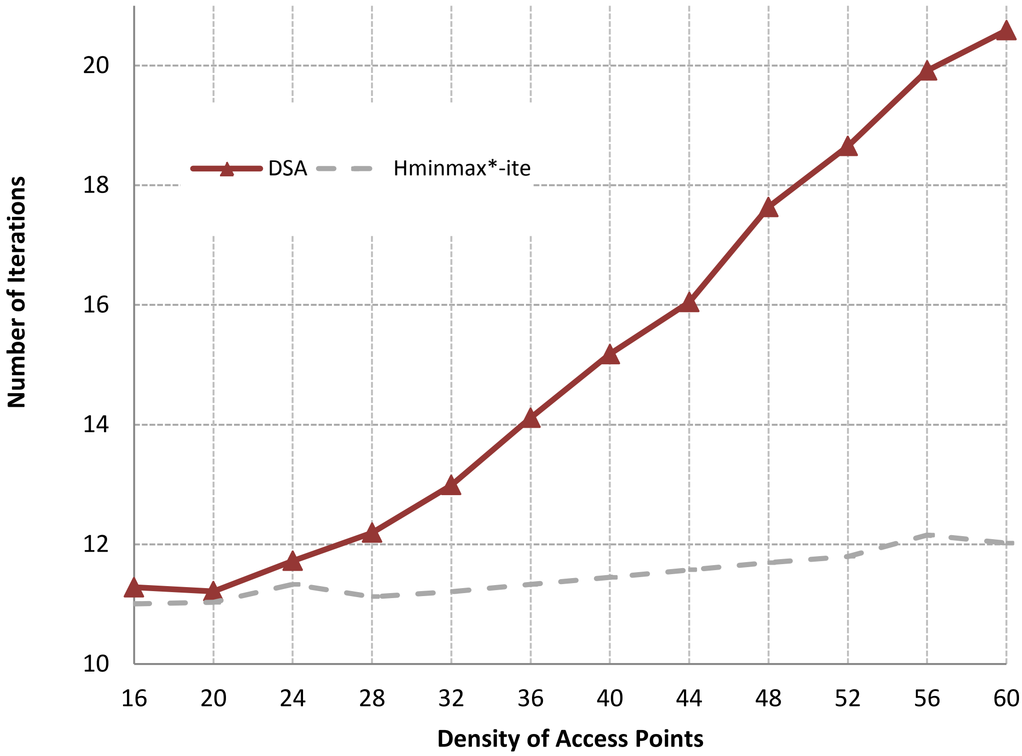


Figure 5.39: Number of Iterations versus Density of APs, for Distributed Algorithms

Figure 5.40 indicates the number of changes of channels per AP for different densities of APs. From this figure, it can be observed that the number of changes of channels performed by each AP in DSA is greater than Hminmax*-ite. This fact is due to the greater number of iterations performed by DSA.

Notice that, for lower number of APs, the number of APs changing channels is not the lowest, which is caused by the configuration established for DSA. Because the probability of accepting a candidate channel with a greater penalty is high, this one has been configured for a larger set of APs operating in the scenario.

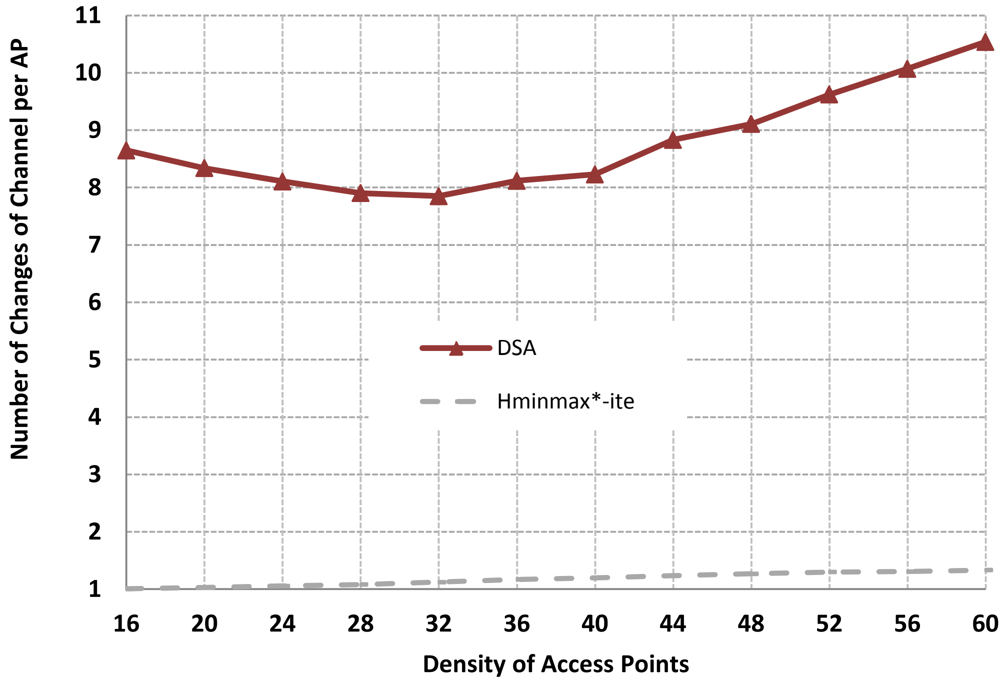


Figure 5.40: Number of Changes of Channel per APs versus Density of APs, for Distributed Algorithms

2. *Performance Assessment*

Results of these simulations have been obtained considering 20 PUs in the scenario. Figure 5.41 provides the percentage of feasible APs for different densities of APs within the scenario. As shown in the figure, the best performance is the one obtained by DSA. For example, for 60 APs, DSA is able to provide around 5 percentage points more of feasible APs than Hminmax*-ite.

Figure 5.42 shows the percentage of APs using primary band required for obtaining the feasible APs shown in Figure 5.41. This figure illustrates that the percentage of APs using primary band for the DSA algorithm is always much lower than the reference technique. For instance, for 60 APs, DSA has 12 percentge pints less of APs using PB than with Hminmax*-ite. In conclusion, the prioritization of the ISM band in the DSA algorithm allows the APs to be less dependent on the primary channels, and, consequently, makes for a more efficient use of the ISM band.

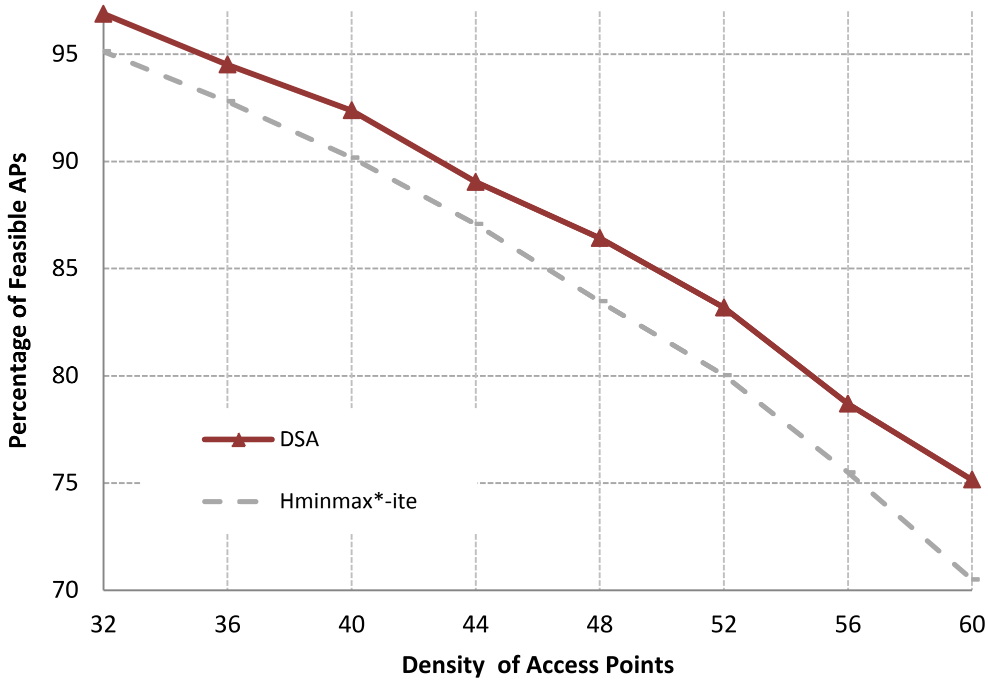


Figure 5.41: Percentage Feasible APs versus Density of Access Points, for Distributes Algorithms

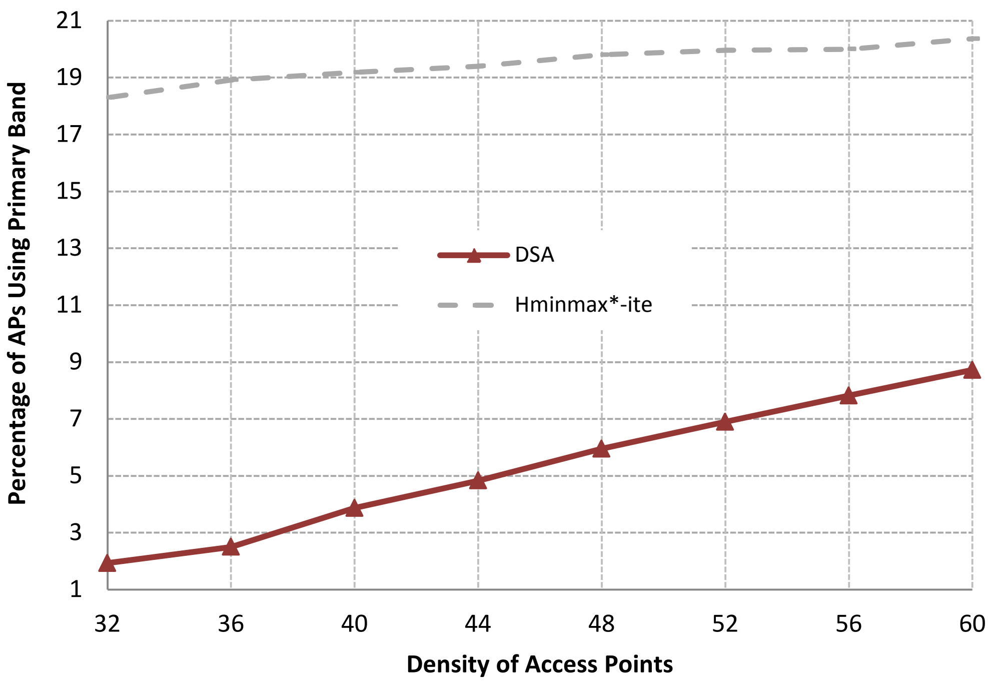


Figure 5.42: Percentage APs Using Primary Band versus Density of Access Points, for Distributed Algorithms

In the following figures, an analysis of the algorithms' performance is demonstrated in terms of the penalties in the network scenario considering ISM and primary bands separately.

Figure 5.43 illustrates the percentage of edges with a penalty greater than zero for different densities of APs in the scenario. It is appreciated in Figure 5.43a that the ISM band concentrates a higher percentage of edges with a penalty greater than zero than the primary band as shown in Figure 5.43b. So, for instance, for 44 APs, DSA produces around 36.5% of edges with a penalty higher than zero in the ISM band and 0.14% in the PB.

DSA generates a lot more edges with $P > 0$ in ISM band than the Hminmax*ite, although in the primary band, the opposite behavior is observed. Thus, DSA tries to balance the penalty between the different edges in the ISM band, in order to use the primary band as little as possible.

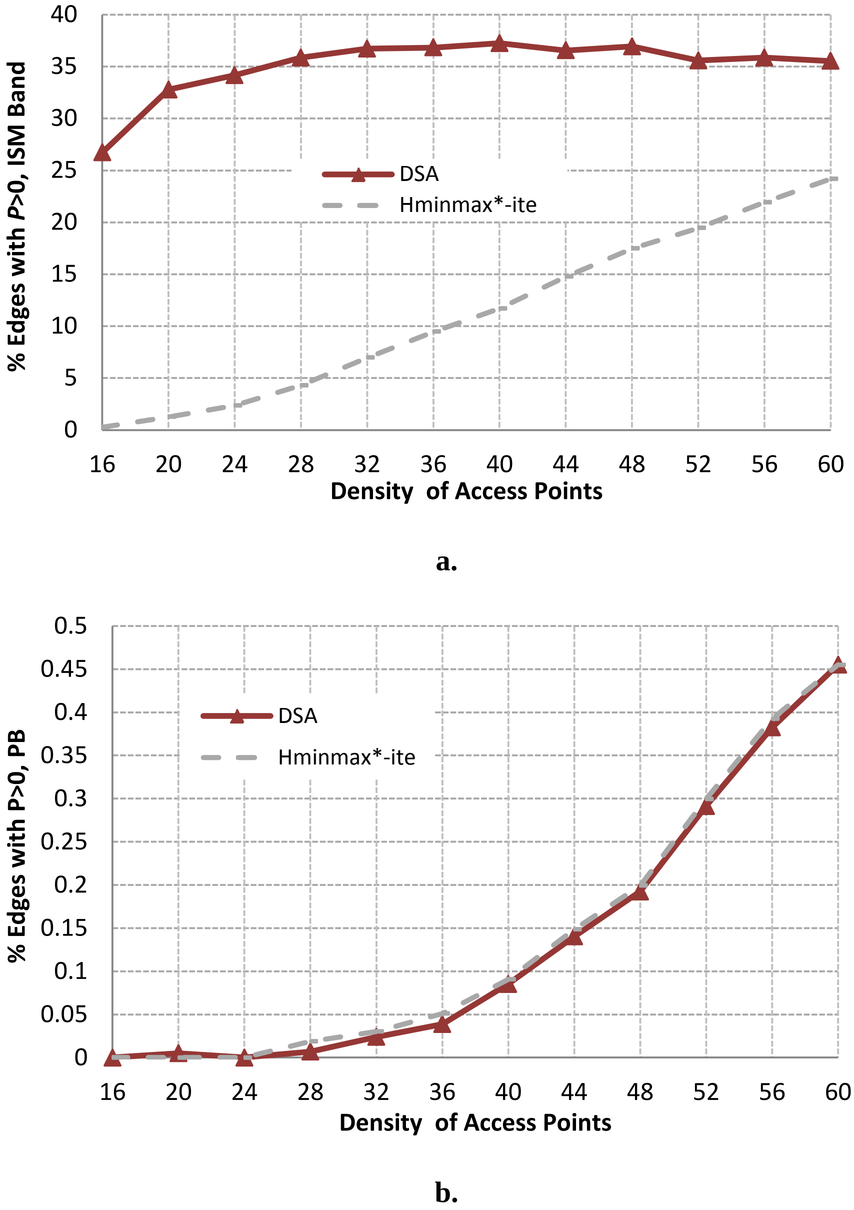
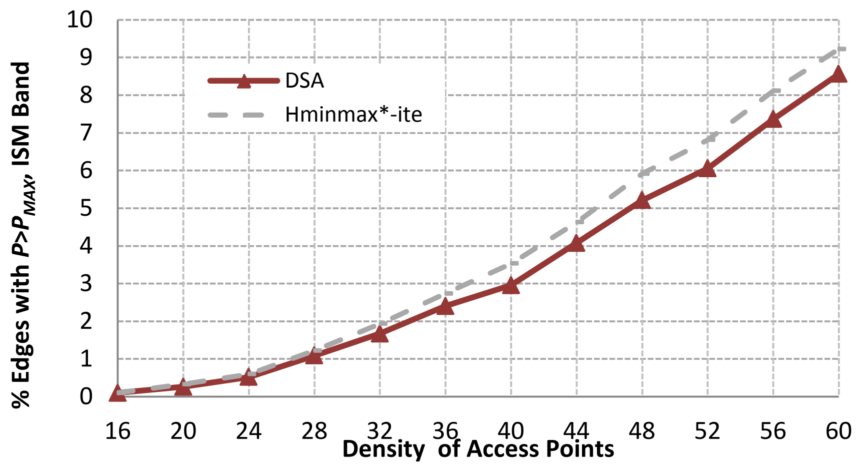


Figure 5.43: Percentage of Edges with Penalty greater than zero in the Scenario versus Density of APs, for Distributed Algorithms

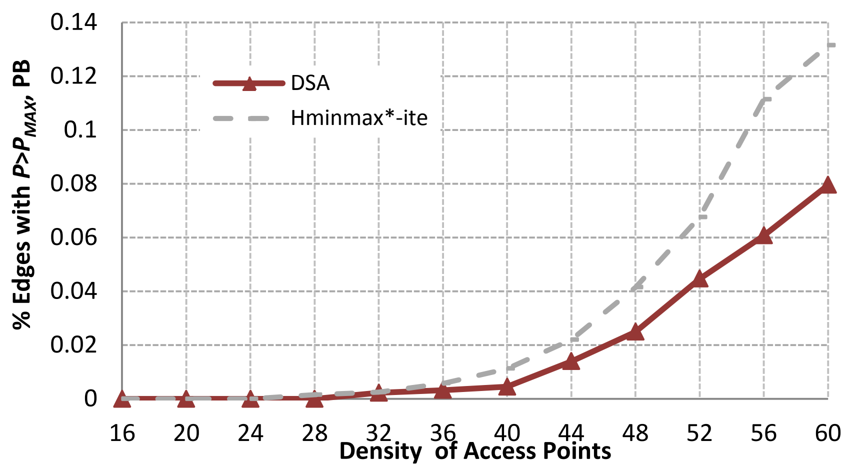
Figure 5.44 depicts the percentage of edges with $P>P_{MAX}$ for ISM band and primary band. The percentage for the ISM band illustrated in Figure 5.44a is much higher than the one obtained in the primary band shown in Figure 5.44b. These results are similar to those obtained for CSA.

Figure 5.44a indicates that DSA obtains a lower percentage of edges with $P>P_{MAX}$ in ISM than Hminmax*-ite. This fact confirms the obtained feasibility results shown in Figure 5.28, since the algorithm with a lower percentage of edges with $P>P_{MAX}$ obtains a higher percentage of feasible APs.

Therefore, the APs operating in the ISM band are responsible for the decrease of feasibility in the algorithms, since the percentage of edges with $P>P_{MAX}$ in the ISM is much higher than in the primary band, so that the percentage of edges with $P>P_{MAX}$ in the primary band has little effect on the feasibility of the algorithms. For example, for DSA with 44 APs, this percentage is about 4% in ISM band and 0.013% for primary band.



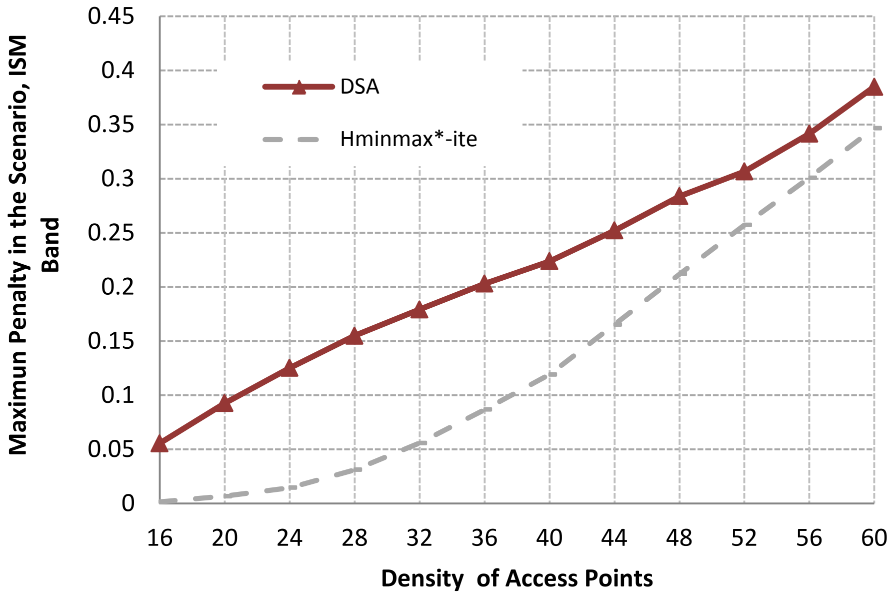
a.



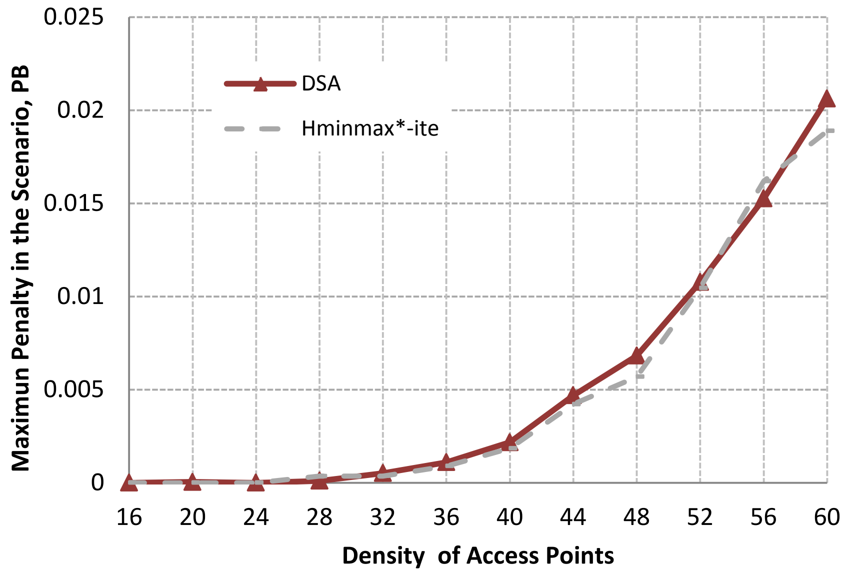
b.

Figure 5.44: Percentage of Edges with Penalty greater than the Penalty Maximum in the Scenario versus Density of APs, for Distributed Algorithms

As seen in Figure 5.45a the maximum penalty from all the edges in the scenario in the ISM band is obtained by DSA. This fact does not represent a lesser number of feasible APs when DSA is compared to Hminmax*-ite, because, as depicted in Figure 5.44a, the percentage of edges with $P>P_{MAX}$ for DSA is the lowest. In the primary band, the two algorithms have a similar behavior and the maximum penalty is in average always lower than the P_{MAX}.



a.

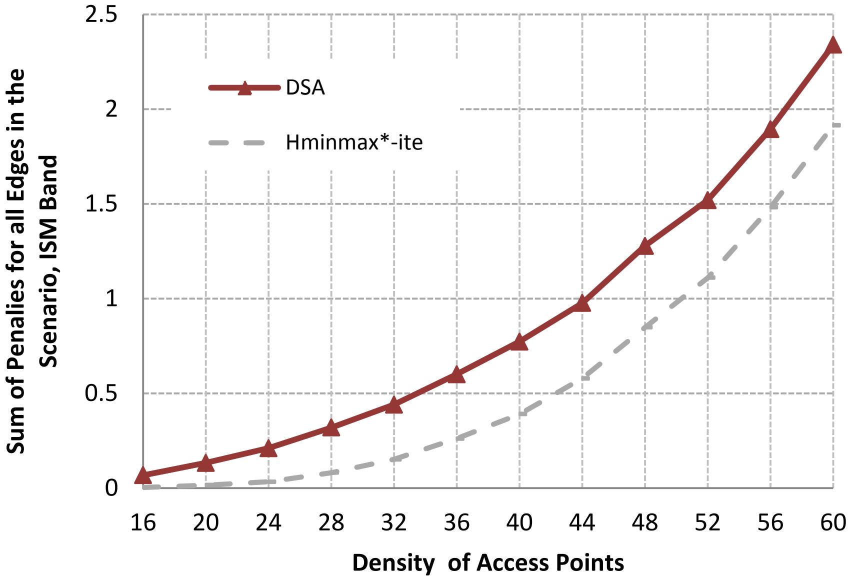


b.

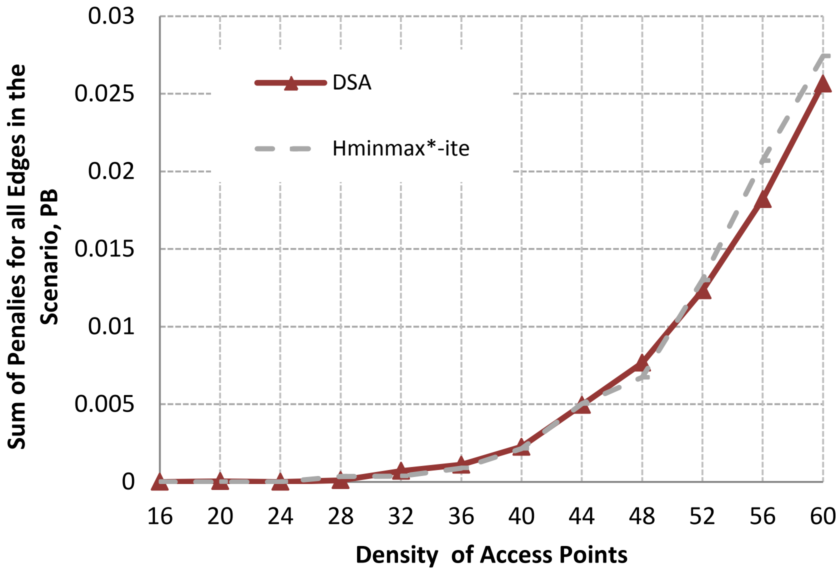
Figure 5.45: Maximum Penalty in the Scenario versus Density of APs, for Distributed Algorithms

Figure 5.46 exposes the sum of penalties of edges in the entire scenario for ISM and primary bands with respect to different numbers of APs.

Figure 5.46a allows us to appreciate that, for the DSA algorithm, the sum of penalties for all the edges in the scenario in the ISM band is greater than Hminmax*-ite. This fact is caused by the largest number of edges with a penalty greater than zero being generated by this algorithm, as shown in Figure 5.46a. Figure 5.46b illustrates a similar behavior for both algorithms in the primary band.



a.



b.

Figure 5.46: Sum of Penalties for all Edges in the Scenario versus Density of APs, for Distributed Algorithms

3. Spectrum Availability in the Network Scenario

Figure 5.47 depicts the percentage of feasible APs and the percentage of feasible assignments (i.e., snapshots with all APs with *P* below P_{MAX}) that are obtained when the spectrum heterogeneity is increased (i.e., density of PUs is increased). The results obtained by DSA are always better than those obtained by the other algorithm. DSA, similar to CSA, has a more stable behavior than the other algorithm for changes in the spectrum heterogeneity, so that the percentage of feasible assignments obtained by DSA decreases more slowly than the reference algorithm.

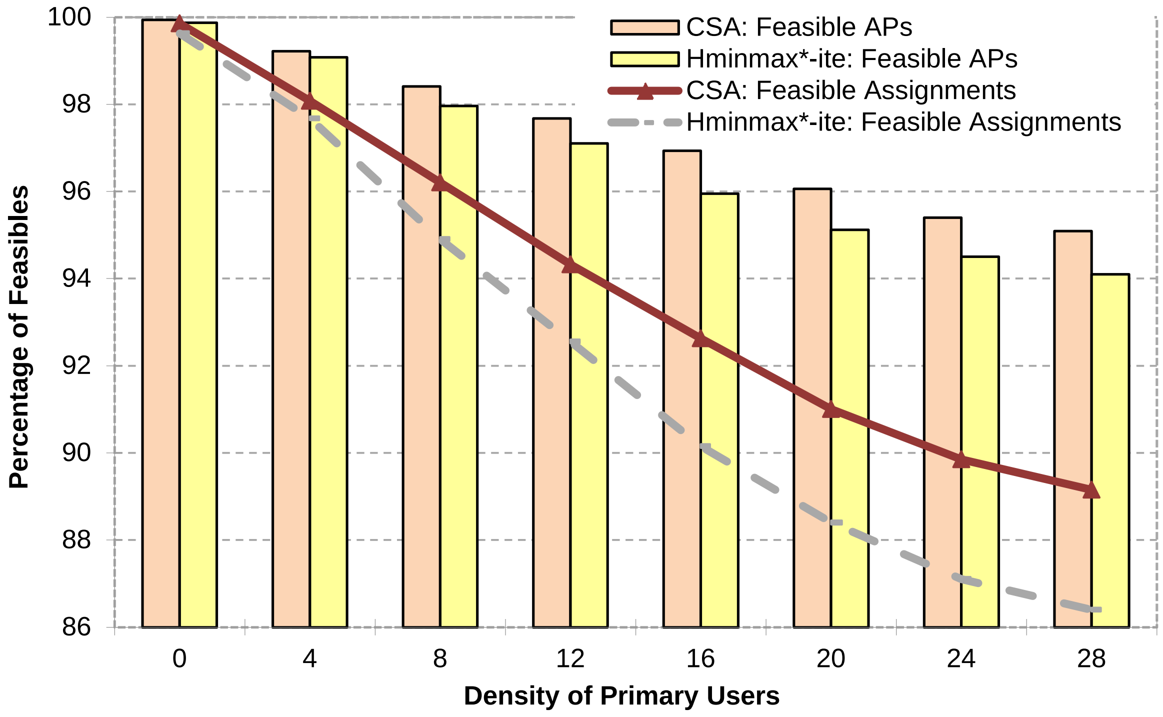


Figure 5.47: Both Percentage of Feasible Assignments and Percentage of Feasible Access Points versus Density of Primary Users, for distributed algorithms, and 32 APs

4. Error Margin Analysis

Figure 5.48 illustrates that the obtained error margin for DSA considering sets of 2000 snapshots is lower than 1%. So, for example, for sets of 2000 snapshots, the obtained error margin is around 0.35%. On the other hand, for sets of 100 snapshots, the achieved error margin is about 2%. Hence, the simulations in this work were performed for sets of 2000 snapshots, because the obtained error margin is the lowest.

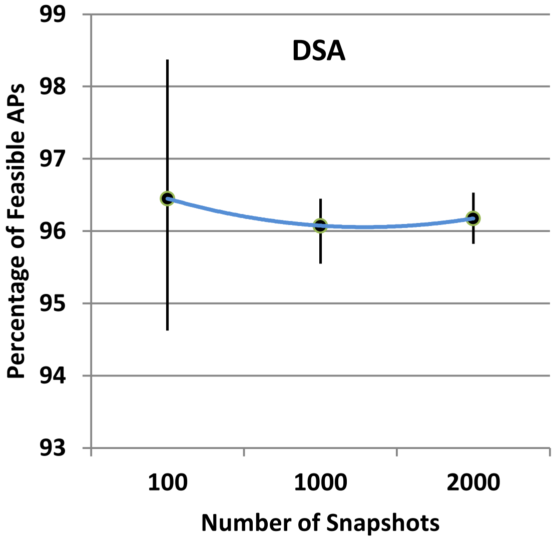


Figure 5.48: Error Margin of the Percentage Feasible APs for Different Number of Snapshots, Considering 10 Samples per Number de Snapshots, 32 APs and 20 PUs

5.8 Conclusion

In this chapter, optimal and heuristic algorithms have been proposed, developed and evaluated according to their performance for the purpose of solving the OSA-enabled WLANs channel assignment problem.

The problem has been formulated as a BLP problem in order to obtain optimal solutions by means of the branch and bound algorithm. This algorithm has a very high computation complexity. This is reflected in the execution times of the algorithm, which can be very high. However, this algorithm is able to achieve optimal results for scenarios with a low number of APs. Also, it can be concluded that when the amount of APs in the scenario increases, the execution times are not long enough to be able to traverse the whole tree.

Then, the problem has been addressed by heuristic algorithms, with centralized and distributed computing approaches.

The centralized algorithms have been successfully proven to obtain a significant number of feasible assignments with a significantly reduced computation complexity when compared to time-consuming branch-and-bound algorithms.

The algorithms are able to efficiently exploit the heterogeneous availability of primary channels in a dense WLAN scenario so that mutual interference between individual WLANs can be reduced.

The algorithms have been shown to considerably increase the number of feasible assignment solutions when compared to assignment solutions that do not exploit spectrum heterogeneity at each AP, while keeping the usage of primary channels very low, thus shielding the channel assignment as much as possible from the temporal and spatial variations of the primary channels' availability. Likewise, the proposed algorithms find more feasible assignments when the heterogeneity of available primary channels increases.

Moreover, for non-iterative proposals, Interf-MST finds better solutions than Dsatur-MST and Hminmax*, in that order. Hence, the criterion used for determining the ordered list in which APs are assigned channels is fundamental in this type of algorithms. On the other hand, for iterative algorithms, CSA obtains the best performance, followed by the Interf-MST-ite and finally by Hminmax*-ite. A less greedy reassignment criterion achieves better results than others who only seek to always benefit.

Also, this thesis has proposed and evaluated the performance of a distributed algorithm (DSA) designed for opportunistic channel assignment in densely uncoordinated WLAN scenarios. The algorithm supports the prioritization of ISM over PB channels and exploits the fact that PB availability is not homogeneous in order to better assign channels to APs. The algorithm has been shown to considerably increase the probability of finding feasible assignment solutions while achieving a low usage of the primary channels compared to an adaptation of other classical WLAN algorithm such as Hminmax*ite.

Chapter 6. **Conclusions**

6.1 Summary

Motivated by the need to improve the overall performance of a high number of APs working in close vicinity, this work has discussed and analyzed the opportunities and challenges associated with the exploitation of OSA capabilities in WLANs.

A massive adoption of WLAN, especially for providing Internet access within residential and office buildings through the deployment of uncoordinated individual APs, can create congestion problems in the ISM bands used for WLAN operation, which, ultimately, may result in both an unpredictable degradation in network performance and unfairness among APs.

Based on the above considerations, this thesis has been focused on achieving three main objectives:

- Analyze the possibility to exploit OSA for short-range radio communications systems within indoor locations in dense urban areas.
- Characterize the scenario and the system model which allow the study of channel assignment algorithms for WLANs in OSA-enabled scenarios.
- Formulate, develop and evaluate novel channel assignment mechanisms, jointly considering available channels in both unlicensed ISM and OSA-enabled bands.

To meet the first objective, an analytical model was proposed for estimating the amount of reusable area where the primary spectrum is available, in order that the opportunistic access by WLANs can be performed. For the second objective, a system model was developed to describe and represent the main components involved in an OSA-enabled WLAN scenario. Finally, several channel assignment mechanisms jointly considering available channels in both unlicensed ISM and OSA-enabled licensed bands were formulated. Optimal and heuristic solutions were proposed and evaluated by considering centralized and distributed solutions. These objectives were achieved by developing analytical models and algorithms, which were then evaluated through computer simulations. The main contributions obtained by the attainment of the proposed objectives and some perspectives of future works are presented below.

6.2 Contributions

A first contribution consists of the identification and quantification of the locations within indoor locations in dense urban areas, where short-range radio communications systems enabled with OSA capabilities can have the possibility of exploiting certain spectrum licensed to other systems.

For this analysis, addressed in Chapter 3, the considered scenario reflects the co-existence of primary and secondary wireless communications systems. The former are assumed to provide outdoor coverage through the use of BSs on the roofs of the buildings and customer premise equipment (CPE) with directional antennas placed either on flat roofs or on outside walls of the buildings and half-duplex communication. Also, a typical building layout for dense urban areas was considered, relying on well-known propagation models to characterize outdoor and indoor propagations as well as building penetration. A key point in this analysis is the definition of the two conditions for spectrum reuse. This definition is the cornerstone on which this and the following chapters are supported to determine the availability of spectrum in certain bands. In particular, in Chapter 3, four different conditions for spectrum reusability have been identified according to the different types of interferences arising in the scenario.

To compute and evaluate the amount and spatial distribution of the reusable area within indoor locations, both LOS and non-LOS cases was analyzed. For both cases, obtained results determined that the interference from CPEs to secondary users is the most restrictive condition for finding reusable area. Also, conditions that consider transmission from secondary users to primary devices are less restrictive because of the short coverage of secondary transmitters

The spatial availability of the primary band on each floor of the buildings is very limited on the upper floors due to the fact that: (a) higher floors are exposed to higher interference from the primary transmissions, and (b) the secondary transmissions are prone to generate interference on primary receivers that are located on the roof of the building. On the other hand, the reusable area is available inside of the buildings due to: (a) transmissions from primary and secondary systems are highly attenuated by the walls and windows outside the buildings; (b) in the buildings close to the BS, the CPEs transmit with less power, causing less interference. Because of that, the reusable areas are greater on lower floors, given that the different obstacles in the trajectory of the signals are considered by the propagation models used. Also, the reusable area can be affected by variations in the protection margin of the secondary users (MSU). Thus, if MSU is increased, then the APs are more susceptible to interference from primary devices and, therefore, the least amount of reusable area is achieved. Otherwise, if the interference perceived in SUs from PUs is less than SSU-MSU, the reusable area is increased when MSU is reduced.

By reducing the CPE azimuth angle ($HPBW\ Az_{CPE}$) on the horizontal plane, an average increase in reusable area can be obtained over all floors. However, this angle reduction entails that the installation of the antenna be more thoroughly done and that the maintenance of the antennas be carried out continuously in order to maintain their directivity.

If the percentage of CPEs in the scenario is reduced, the reusable area can be increased by around 21.53 percentage points by reducing the number of CPEs from 100% to 8%, since the interference from CPEs to SUs is the most restrictive condition in determining the reusable area, if the percentage of CPEs in the scenario is reduced

For the NLOS case, the obtained results depicted that the reusable area shows irregular shapes and is located in different places than for the LOS case, caused by the random locations of CPEs in the scenario and the increase in the number of BSs in the scenario. Because of that, the interference condition can be fulfilled in the centers of the buildings and zones that are far from the BSs. The total reusable area obtained by the NLOS case is similar to that which is found in the LOS case. However, for the LOS case, the reusable area is concentrated on the lower floors; in contrast, in the NLOS case, this area is distributed a little more evenly among all the floors.

A second contribution presented in Chapter 4 is the development of the system model needed for the evaluation of channel assignment algorithms in OSA-enabled WLAN scenarios. This system model is built on the concepts of coverage and interference areas, which are established based on propagation and interference models.

The metric called penalty (P) is defined in order to quantify the interference level between APs. This metric is used in the following as the main tool for measuring the interference between devices when they are using a certain pair of channels.

A set of primary band availability conditions are determined, so that a list of available primary channels for each AP can be obtained. These conditions are based on the conditions of spectrum reuse defined in Chapter 3. The constraint for the usage of channels by APs was defined based on penalties between APs; however, these could be defined in terms of other network parameters. Also, the network scenario is represented as a graph with the goal of facilitating the performance evaluation of the channel assignment algorithms.

In order to evaluate the performance of the system model by computer simulations, a case study was analyzed. Obtained results determine that, for a high density of APs in the scenario, the probability that an AP has more neighbors is higher than for low densities. This is mainly due to the fact that, for a higher density of APs, the overlapping between the usage and interference areas from the APs also increases. Also, for a low density of APs, the probability that an AP has zero neighbors is greater than in a high density situation. The maximum number of available channels with a mask of 22 MHz in the primary band is 6. As in the ISM band, these 6 channels are overlapping. However, only two channels are not overlapping; hence, taking into account both ISM and primary bands, each AP could have up to 17 overlapping channels and 5 non-overlapping ones. For a reduced number of PUs, the probability of the APs having 100% of the available primary channel is higher than for scenarios with a higher number of PUs. Also, if more primary users are deployed in the scenario, the probability of obtaining different sets of available channels at each AP increases, i.e. the spectrum heterogeneity increases. Also, it is concluded that the availability of primary channels for the APs decreases as the primary usage radio increases; this is caused by the increase in overlapping areas among devices.

The final and main contribution of this thesis was presented in Chapter 5 and consists of the formulation, development and evaluation of several novel algorithms for solving the channel assignment problem, which jointly consider available channels in both unlicensed ISM and OSA-enabled licensed bands. Both centralized and distributed computing approaches are covered.

A new feature of these algorithms is that, given their nature of operating in two bands, the channel prioritization and the spectrum heterogeneity need to be considered in the problem formulation.

In this way, the OSA-enabled WLANs channel assignment problem is stated in order to find a proper channel assignment for each AP that satisfies two main objectives: a) the penalty between any pair of APs $P(ap_u^i, ap_v^j)$ is kept below a certain maximum penalty (P_{MAX}); b) the number of APs using channels in the primary band is minimized.

The channel assignment problem was firstly formulated as a BLP. Optimal solutions were obtained by means of the BB algorithm, which has been shown to have very high computation complexity to cope with a high number of APs. In these cases, when a maximum execution time is set out, it's been observed that solutions found by the BB may not be the optimal ones because the algorithm cannot traverse the whole and, consequently, the use of the primary band can be penalized.

Motivated by the need to have more computationally efficient solutions, three centralized heuristic algorithms were proposed (Interf-MST, Dsatur-MST and CSA). Two of them are based on building a Minimum Spanning Tree (MST) graph of the weights associated with the edges, and the third is based on Simulated Annealing techniques. In addition, a distributed adaptation of the simulated annealing (DSA) algorithm was proposed. To benchmark these algorithms against existing solutions, an adaptation of the Hminmax algorithm was developed.

Centralized algorithms have been successfully proven to obtain similar results to those achieved by the BB algorithm in terms of feasible assignments and primary band use with much less computation complexity.

For non-iterative proposals, Interf-MST finds better results than Dsatur MST and Hminmax*, in that order. Hence, the criterion used for determining the ordered list in which APs are assigned channels is fundamental in these types of algorithms. Also it can be concluded that, the algorithms that exploit the spectrum heterogeneity at each AP found better solutions of feasible assignment and feasible APs than those that do not exploit spectrum heterogeneity at each AP. Algorithms with prioritization of ISM band make reduced use primary band compared to algorithms that do not implement this priority, however these achieve more percentage feasible APs, so that make more efficient use of the available channels. The algorithms that consider both spectrum heterogeneity and band prioritization found more feasible assignments than the algorithms with others combinations.

On the other hand, for iterative algorithms, CSA obtains a better performance in terms of feasibility and usage of primary band than the Interf-MST-ite and Hminmax*-ite. This is due to the fact that CSA is not a greedy algorithm, since it allows the APs to be assigned channels at each iteration that do not improve their penalties. On the other hand, Interf-MST- ite and Hminmax*-ite follow a greedy strategy, since they only allow channels to be assigned that improve their penalties, so that the criterion used by these two algorithms limits the reassignment of channels at each iteration. Consequently, the number of iterations performed by CSA is much larger than the one done by other algorithms.

CSA tries to balance the penalty between the different edges in the ISM band in order to use the primary band as little as possible, since CSA generates significantly more edges with $P > 0$ in the ISM band than the other algorithms, although in the primary band, the opposite behavior is observed. However, CSA obtains the least percentage of edges with $P > P_{MAX}$ in ISM followed by Interf-MST and Hminmax*, in that order. This fact confirms the obtained feasibility results because the algorithms with a lower percentage of edges with $P > P_{MAX}$ obtain a higher percentage of feasible APs.

The Interf-MST-ite obtains a percentage of edges with P>0 greater than the other algorithms in the primary band. This behavior is because the weights used to build the MST depend on both the λ and P between APs, so that the APs with a lower availability of primary channels are assigned first and, with preference, to the ISM band channels rather than the APs with a greater availability of primary channels. So, when the APs want to reassign channels, they will see the ISM band as very congested and accordingly will use the primary channels. However, these magnitudes of the penalties in the primary band are very low, and, hence, this usage of the primary band does not represent a risk for achieving the formulated objectives in the channel assignment problem. It is noteworthy that, due to the CSA generating a higher number of edges with $P > 0$ in the ISM band, the sum of edges in the ISM band is also higher than for the other algorithms.

For distributed algorithm, DSA has been shown to considerably increase the probability of finding feasible assignment solutions while achieving a low usage of the primary channels compared to an adaptation of other classical WLAN algorithm such as Hminmax*-ite. Because of the nature of DSA, it has a similar behavior to CSA. However, CSA finds better results in terms of feasibility and usage of the primary band. DSA as CSA generates more edges with $P > 0$ than the other algorithms so that it also balances the penalties between the different edges of the scenario. Nonetheless, DSA has more edges with $P > P_{PMAX}$ therefore reaches a smaller percentage of APs feasible than CSA.

In conclusion, the algorithms that can better balance the penalties between the edges reached more feasible solutions and less use of primary band than the others, so this type of less aggressive algorithm solves in a better way the OSA-enabled WLANs Channel Assignment Problem.

6.3 Future works

Some possible future works can be generated in the wake of this thesis work, and they are listed below:

- The analysis of spectrum availability in urban scenarios deserves further analysis. The contribution of this thesis shows that the determination of the reusable areas is quite dependent on the building layouts, especially across the height component. Hence, the development of more accurate models for these scenarios can eventually contribute to increase the amount of spectrum that is actually made available for secondary access. Field measurements would be necessary to validate the models.
- The system model can be extended by considering traffic and mobility models. This would allow introducing channel assignment constraints based on criteria other than interference such as individual STA and/or aggregated AP throughputs and QoS requirements. On this basis, the new criteria can be considered to reformulate the *P* metric as well as the weights and channel selection functions used in the proposed heuristics. Also, the time variability of users' activity and locations might be accounted though the development of more complex system level simulation models.
- Starting from the DSA proposed in this work, develop and evaluate an extension of this distributed algorithm able to exploit local coordination with APs in close vicinity.

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