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Channel Assignment Algorithms for OSA-Enabled WLANs Exploiting Prioritization and Spectrum Heterogeneity

Francisco NOVILLO[†a)], ***Member and*** **Ramon FERRÚS**[††b)], ***Nonmember***

SUMMARY Allowing WLANs to exploit opportunistic spectrum access (OSA) is a promising approach to alleviate spectrum congestion problems in overcrowded unlicensed ISM bands, especially in highly dense WLAN deployments. In this context, novel channel assignment mechanisms jointly considering available channels in both unlicensed ISM and OSA-enabled licensed bands are needed. Unlike classical schemes proposed for legacy WLANs, channel assignment mechanisms for OSA-enabled WLAN should face two distinguishing issues: channel prioritization and spectrum heterogeneity. The first refers to the fact that additional prioritization criteria other than interference conditions should be considered when choosing between ISM or 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 users' activity in the OSA-enabled bands. This paper firstly formulates the channel assignment problem for OSA-enabled WLANs as a Binary Linear Programming (BLP) problem. 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, a novel channel assignment algorithm based on weighted graph coloring heuristics and able to exploit both channel prioritization and spectrum heterogeneity is proposed. The algorithm is evaluated under different conditions of AP density and primary band availability.

key words: *binary linear programming, channel assignment, channel prioritization, OSA, spectrum heterogeneity, WLAN*

1. Introduction

Highly dense deployments of Wireless Local Area Networks (WLANs) arisen from e.g. multiple individual WLAN installations in residential buildings as well as large-scale WLAN deployments in enterprises or campuses, are leading to excessive levels of interference in unlicensed bands that, ultimately, may turn into performance degradation of such networks. In these scenarios, channel assignment mechanisms constitute the main tool to reduce 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 5 GHz ISM bands) has received a lot of attention in the research community [1]–[4]. 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 OSA-enabled bands and use them without causing interference to primary users (PUs) holding spectrum usage rights in the bands.

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 [5], [6]. 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 [7] show that this licensed band could still be opportunistically reused within indoor building locations where many WLAN are expected to operate. This fact has led to the consideration of unlicensed access by WLAN devices in some research works and market initiatives [8], [9]. As an example, White-fi is a term being used to describe the use of a Wi-Fi technology within the TV unused spectrum, or TV white space. The IEEE 802.11af [8] 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 primary band.

Unlike the channel assignment problem in legacy WLAN restricted to the usage of ISM bands, the OSA-enabled channel assignment problem shall face two distinguishing issues:

- Channel prioritization: prioritization criteria other than interference conditions should be considered when choosing between an unlicensed and an opportunistic channel. Hence, as an example, it could be considered that, under the same interference conditions, an ISM channel is preferred to a primary band channel in order to decouple as much as possible channel assignment solution from primary

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[†] The author is with Electrical and Computer Engineering Department, Escuela Superior Politécnica del Litoral, ESPOL, campus Gustavo Galindo, Km 30.5 vía Perimetral, apartado 09-01-5863, Guayaquil, Ecuador.

[††] The author is with Signal Theory and Communications Department, Universitat Politècnica de Catalunya, UPC, Jordi Girona 1-3, Barcelona, Spain.

a) E-mail: fnovillo@espol.edu.ec
b) E-mail: ferrus@tsc.upc.edu

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user activity. This possibility turns the channel assignment problem into an assignment problem where channels do not have the same priority to be used, as opposed to what is considered in traditional WLAN assignment problems.

- 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 where it is assumed that all APs have the same spectrum availability.

Upon such a basis, this paper firstly formulates the channel assignment problem in an OSA-enabled WLAN deployment as a Binary Linear Programming (BLP) problem in order to obtain optimal solutions. The BLP problem is aimed at keeping interference levels between APs below a certain interference threshold. It is considered that the APs can use a channel among those existing within the ISM band or, under some circumstances, a channel within an additional frequency band (i.e. primary band) licensed to other services (i.e. primary users). The conditions to determine the availability of these additional primary channels are considered 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). Furthermore, it is considered that use of the primary band to alleviate congestion in the ISM band should be kept as low as possible, thus shielding the channel allocation from the temporal and spatial variations of the primary channels' availability as much as possible. Algorithms to optimally solve this kind of optimization problem exist (e.g. branch and bound algorithms), but they are not efficient for a large number of APs, given that these require high computational efforts.

Hence, in this paper, the formulated channel assignment problem is solved by means of a heuristic algorithm based on weighted graph coloring techniques [10] that exploits both channel prioritization and spectrum heterogeneity with short execution times. In particular, the algorithm obtains a channel assignment by building a Minimum Spanning Tree (MST) graph where APs are vertices; edges between APs represent some degree of interference between APs and weights associated with the edges account for both primary channel availability and interference conditions among APs. Results are provided to assess the benefits of such a proposal under different WLAN deployment densities and primary spectrum availability conditions.

1.1 Related Works

In order to obtain an improvement of performance in WLANs, different algorithms have been proposed to solve the channel allocation problem, with the objective of diminishing the impact caused by the reuse of channels. Thus in [1], [2] the channel assignment problem is formulated as an integer linear programming (ILP) problem. In the first, the authors propose an ILP 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. In the second, the ILP problem is formulated to fulfil 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 in [9], 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. Our work differs from the aforementioned ones in the optimization objective that minimizes the use of PB. Authors in [14] and [15] formulate the channel allocation problem as a non-ILP problem in order to maximize the utilization of the spectrum by considering an opportunistic scenario. Additionally, neither work considers overlapping among channels. Hence, the main difference from the above proposals is the problem formulation, since they do not consider spectrum heterogeneity and channel prioritization.

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 [4]. Also, a survey on the channel assignment problem in wireless networks including those with opportunistic access can be found in [16].

The remainder of the paper is organized as follows. Section 2 describes the system model characterization. In Sect. 3, the channel allocation problem is formulated as a BLP problem. The graph-theoretic formulation is described and the proposed algorithm is detailed in Sect. 4. The performance evaluation of the proposed algorithm is provided in Sect. 5. Finally, concluding remarks and future work are stated in Sect. 6.

2. System Model

2.1 Network Scenario

The considered network scenario consists of a set of individual APs (with their associated WLAN client stations) deployed in a limited geographical area. Each AP is expected to operate on an ISM channel or a channel available for opportunistic access in a licensed (primary) band. Licensee users of the primary band are referred to as primary users (PUs) while APs are secondary users (SUs) that can only use that band whenever the operation of PUs is not impaired. Note that channelization used by WLAN in the primary band (PB) could be different from that used by PUs. Figure 1 illustrates the envisioned scenario where a dense deployment of OSA-enabled APs co-exists with a primary system in the same geographical area.

2.2 Primary Band Availability Conditions

Availability of primary channels to SUs (i.e. APs) is modeled according to the locations and the potential interference

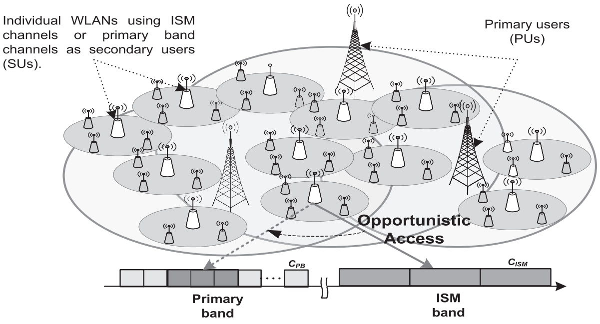

Fig. 1 Network scenario.

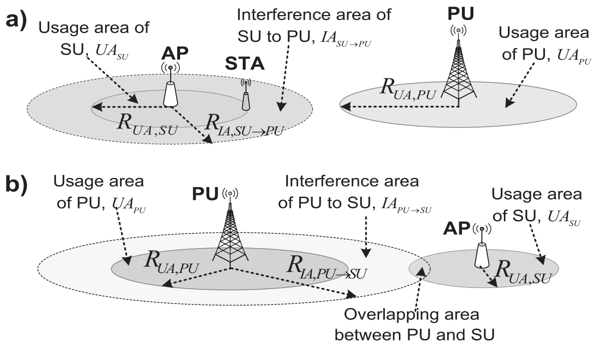

Fig. 2 Interference conditions: a) From WLAN to PUs, b) From PU to WLANs.

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. Hence, an SU can use a given primary channel whenever the interference received by any PU receiver tuned to that channel, I_{SP}, is below the PU receiver sensitivity S_P minus a given protection margin M_P. This usage condition imposed on SU transmitters can be formulated as $I_{SP} \leq S_P - M_P$. Additionally, the successful operation of SU receivers tuned into primary channels also requires interference received from PU transmitters, I_{PS}, to be lower than SU receiver sensitivity minus a protection margin of M_S. Hence, the usage condition required by SU receivers can be formulated as $I_{PS} \leq S_S - M_S$. It is worth noting that both receiver protection margins, M_S and M_P, would account for the fading margin along with the minimum required signal-to-interference ratio. The two usage conditions can be used to define a set of usage and interference areas for PUs and SUs. The usage area is the coverage area of a given service. Interference area represents the spatial area in which a receiver would be exposed to an unacceptable level of interference generated by a transmitter. Hence, considering omnidirectional antennas and homogeneous propagation conditions, spatially, these areas would be circular in shape, as illustrated in Fig. 2.

Assuming a propagation model characterized by channel attenuation at 1 m (L_o) and propagation slope α, the radius for the usage area ($R_{UA,x}$) is computed by means of the following expression: $R_{UA,x} = 10^{\frac{(P_X - S_X) - Lo}{10\alpha}}$, in which x can be either PU or SU, and the pair (P_x, S_x) is the transmitted power and sensitivity of the considered system. Building upon the concepts of usage and interference areas, a Penalty (P) factor 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:

$$P(y^i, z^j) = \frac{\left[UA_z \cap IA_{y\to z}\left(\rho_{y^i \to z^j}\right)\right]}{UA_z} \tag{1}$$

in which y and z represent the interfering and interfered with device respectively, which can be either PU or SU. UA is the usage area of z and IA is the interference area between y and z. i, j correspond to transmitter and 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 developed in [17].

Relying on the P factor 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 usage area of a PU must not overlap with the interference area of an SU (i.e. $P(PU^i, SU^j)$=0). Thus, since PUs have priority use on the primary band, the SUs are not allowed to cause interference within the coverage range of the PUs, as shown in Fig. 2(a).

b) 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}), (i.e. $P(PU^i, SU^j) \leq P_{MAX}$). If $P_{MAX} > 0$, it means that the SU is allowed to operate, even under the presence of some amount of interference coming from PUs, as shown in Fig. 2(b).

2.3 Channel Assignment Constraints

The P factor is also used to establish channel allocation constraints for the individual WLAN networks. 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: $P(ap_u^i, ap_v^j) \leq P_{MAX}$. The same condition applies regardless of whether the channels being considered are ISM or PB channels.

3. Problem Formulation and Optimal Solution

In this section, the channel assignment problem for OSA-enabled WLAN deployments is formulated as a Binary Linear Programming (BLP) problem in order to obtain optimal solutions. The objective is to find a proper channel assignment for every AP so that the number of APs using channels in the primary band is minimized and the penalty factor between any pair of APs $P(ap_u^i, ap_v^j)$ is below a certain threshold P_{MAX}. The latter objective is defined as the channel assignment constraint among APs. For that, the spectrum availability at each AP and the penalties between APs are considered as input parameters. The rationale behind pursuing the minimization of primary band use is related to

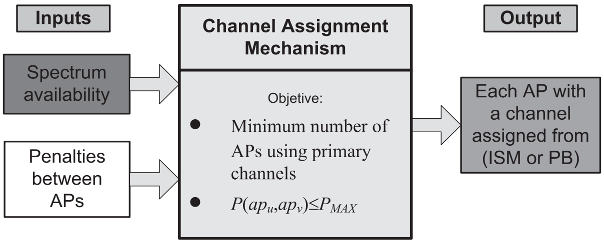

Fig. 3 Channel assignment scheme.

the need for finding a solution with low dependability on the presence of primary users. The conditions to determine the availability of these additional primary channels are considered 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). Figure 3 shows a scheme of the proposed problem.

3.1 Binary Linear Programming (BLP) Problem Formulation. Optimal Solution

The following notation is defined in order to formulate the BLP problem. For every AP, ap_u, a channel i must be chosen from among a set C_T of potential channels: C_{ISM} that contains all the ISM channels plus an additional set C_{PB} of the primary channels that may be exploited as secondary users (i.e. $C_T = C_{ISM} + C_{PB}$). The numbering of the channels is done 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 imparing the operation of primary users) for AP u is represented by vector $A(ap_u) = \left\{ a_{ap_u^i} \left| a_{ap_u^i} \in \{0,1\} \forall 1 \le i \le |C_T| \right. \right\}$ 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 considered to be always available while PB channel availability will depend on primary user activity and interference conditions formulated in Sect. 2.1. Hence, the channel selection for a given AP ap_u is represented by means of binary variables defined as:

$$x_{ap_u,i} = \begin{cases} 1; & \text{if } i \text{ is assigned to } ap_u \text{ and } a_{ap_u^i} = 1, \\ & \forall i \in C_T \\ 0; & \text{otherwise} \end{cases} \tag{2}$$

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

$$\min \left(\sum_{u=1}^{N} \sum_{i=|C_{ISM}|+1}^{|C_{ISM}|+|C_{PB}|} X_{ap_u,i} \right) \tag{3}$$

Subject to the following constraints:

$$\sum_{i=1}^{|C_{ISM}|+|C_{PB}|} x_{ap_u,i} = 1; \forall u = 1, 2, \ldots, N \tag{4}$$

$$x_{ap_u,i} + x_{ap_v,j} \le 1 \text{ if } P(ap_u^i, ap_v^j) > P_{MAX} \tag{5}$$

for

$$\begin{aligned} & u, v \in \{1, \ldots, N\} \\ & i, j \in \{1, \ldots, |C_{ISM}| + |C_{PB}|\} \end{aligned} \tag{5.1}$$

in which (3) represents the objective function that minimizes the use of the primary channels. Constraint (4) indicates that a single channel is used per AP. Expression (5) accounts for the channel assignment constraint between each pair of APs. This constraint ensures that both channel i and j cannot be assigned to AP u and v respectively when the penalty factor between both is above the P_{MAX}. Expressions in (5.1) denote that the set of APs is of size N, and the potential channels for each AP.

BLP problems can be solved by using algorithms (e.g. Branch and Bound algorithm) capable of finding optimal solutions if they exist. However, in a previous work [11], 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. For instance, a measure of the complexity to solve these problems could be the total number of variables (i.e. $x_{ap_u,i}$) required to obtain optimal solutions that are given by $N \times (|C_{ISM}| + |C_{PB}|)$. Therefore, in scenarios with a high density of APs, finding optimal solutions to the channel allocation problem can require very high computational efforts. In any case, branch and bound algorithms are used as a benchmark for performance evaluation of proposed heuristics addressed in the following.

4. Channel Assignment Mechanism

Since the algorithm used to solve the BLP problem requires long computational times, in this section, a channel assignment mechanism that satisfies the same objective set for the BLP problem and that exploits both channel prioritization and spectrum heterogeneity is developed by means of a heuristic algorithm. This algorithm is built upon weighted graph coloring techniques, which have already proved to be efficient for the classical channel allocation problem [10].

4.1 Graph Theoretic Formulation

The proposed channel assignment mechanism is formulated as a weighted graph coloring problem. The WLAN network deployment is represented as a graph $G = (V, E)$, in which the vertices $V = \{ap_1, ap_2, \ldots, ap_N\}$ correspond to the N APs, and the edges $E = \{e_{u,v} = (ap_u, ap_v) | e_{u,v} \in \{0,1\}\}$ account for the interference conditions between the APs. In particular, an edge between two APs exists if the P factor calculated under co-channel conditions is greater than zero. The APs linked by an edge are defined as neighbors. The color or channel eventually assigned to AP u by the algorithm is represented by $Ch(ap_u)$. In the rest of this paper, APs and vertices and, similarly, colors and channels will be used interchangeably.

4.2 Algorithm Description

The proposed algorithm assigns each AP a channel (either from ISM band or primary band) in a certain order. The order in which each AP is colored depends on the weight of the edges among APs that account for the spectrum availability and the penalties between each of the 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. Hence, an MST is a spanning tree with a weight less than or equal to the weight of every other spanning tree. A similar approach for using the MST was considered in [2]. The algorithm is based on Prim's algorithm to find the MST of a given graph [18]. 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. Notice that, while the MST is being built, the spectrum heterogeneity is exploited, since the weight of the edges considers the availability of channels at each AP, as explained below. 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.

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 $\lambda(ap_v)$, and the penalty factor P between APs u and v in co-channel conditions, according to the following expression:

$$W(ap_u, ap_v) = \lambda(ap_v) \cdot P\left(ap_u^i, ap_v^j\right), \quad \forall i = j \tag{6}$$

The introduction of the channel availability factor λ is intended to account for the different suitability that each particular AP may have as to the potential use of primary band channels (i.e. spectrum heterogeneity). This factor is formulated as a decreasing function with respect to 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 to APs with less available primary channels (i.e. these APs will increase the probability of being assigned first since they have more restrictions). In this work, factor λ is computed by using the following decreasing exponential function:

$$\lambda(ap_v) = 1 - e^{s\cdot\left(\sum_{\forall j \in C_{PB}} a_{ap_v^j} - |C_{PB}|\right)} \tag{7}$$

where a slope parameter s is used to adjust the level of sensitivity to the number of available primary channels in AP v (obtained from the sum of the non-zero components of vector A (ap_u) which correspond to primary band channels). 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.

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Algorithm: building of ordered list (MST) of APs
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 ∈ V_n has assigned a channel Ch(ap_u).
1.  $L(ap_u) \leftarrow \lambda(ap_u) \cdot \sum_{\substack{\forall\, ap_u, ap_v \in V \\ \wedge\, i=j}} P\left(ap_u^i, ap_v^j\right)$
        ;L(ap_u) is the product of: Availability of primary channels at AP u and Sum of all overlapping areas between AP u and all other APs, for co-channel conditions
2.  choose $ap_x$ as the first AP such that:
        $L(ap_x) = \max\left(L(ap_u)\right)$
3.  Assign Channel; call the function
4.  Update the vector of APs with channel assigned, $V_n = \{ap_x\}$
5.  while $|V_n| \leq N$
6.      $M(ap_v) \leftarrow \max_{\forall ap_u \in V_n \wedge ap_v \notin V_n} W(ap_u, ap_v)$
            ;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:
            $M(ap_y) = \max\left(M(ap_v)\right)$
8.      Assign Channel; call the function
9.      Add $ap_y$ to $V_n$, and $(ap_x, ap_y)$ to $E_n$
10. end(5)
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Fig. 4 Pseudocode to build the ordered list (MST) of APs.

To continue, the algorithm that describes the building of the MST is detailed in Fig. 4. This algorithm for performing the channel assignment for each AP invokes a function denominated as "Assign Channel" that is shown in Fig. 5. As shown in Fig. 4, 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 input parameter. Hence, the same algorithm can be used to prioritize or not the utilization of 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 highest channel availability factor and highest penalty factor with respect to all the other APs of the scenario. This AP

```
Function: Assign channel
Data: $ap_u$
Result: AP $u$ with an assigned channel $Ch(ap_u)$.
1.  if $ap_x$ is the first AP
2.      $Ch(ap_x) = rand\{1,6,11\}$
        ;choose   randomly from ISM band a non-overlapping channel for assignning to theAP $x$
3.  else
4.      $H(c) \leftarrow \max_{\forall e=(ap_y,ap_v)\in E \wedge c\in C_{ISM}} P(ap_y^c, ap_v^{Ch(ap_v)})$
        ; $H(c)$ is max $P$ of any edge respect to $ap_y$, considering only ISM band
5.      Choose $c_S$ such that:
        $H(c_S) = \min_{c\in C_{ISM}} H(c)$
        ;choose color with the min(max.$P$) between $ap_y$ and its neighbors using ISM band
6.      if (Prior=True and $H(c_S) \le P_{MAX}$) or $\sum_{\forall i\in C_{PB}} a_{ap_y^i} = 0$ ;
        $Ch(ap_y) \leftarrow c_S$ ;if prior is true the channel $C_S$ is directly assigned
7.      elseif $\sum_{\forall i\in C_{PB}} a_{ap_y^i} > 0$ ; Sch= $c_S$ ;   Check_PB=True
            ;Look if the AP $y$ has available primary channels
8.      end(6)
9.      if ( Check_PB=True)
        ;look within the PB if the $P$ achieved in the ISM band exceeds the maximum penalty
10.         $H(c) \leftarrow \max_{\forall e=(ap_y,ap_v)\in E \wedge c\in C_{PB}} P(ap_y^c, ap_v^{Ch(ap_v)})$
            ; $H(c)$ is max $P$ of any edge respect to $ap_y$ using the channel $c$, considering only primary band
11.         Choose $c_P$ such that:
            $H(c_P) = \min_{c\in C_{PB}} H(c)$
            ;choose color with the min (max $P$) between $ap_y$ and its neighbors using PB
12.         if Prior=True and $H(c_P) \le P_{MAX}$ ; $Ch(ap_y) \leftarrow c_P$
13.         elseif   $H(c_S) \le H(c_P)$; $Ch(ap_y) \leftarrow Sch$;
14.         else   $Ch(ap_y) \leftarrow c_P$;
15.         end(12)
16.     end(9)
17. end(1)
```

Fig. 5 Pseudocode of the function "Assign Channel".

is called as 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". 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).

In Fig. 5, the pseudocode required to implement the function "Assign Channel" is shown. This function assigns to each AP a channel, such that, for the first AP, the channel to be assigned is chosen from among the non-overlapping channels from ISM band (i.e. channels without overlap in accordance with the 802.11 standard), such that the channel assigned to ap_x is defined as $Ch(ap_x)$ (line: 2). To determine the channels of the next APs, 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 (3) (line: 4–5).

The channel obtained is denoted as C_S. This one minimizes the maximum interference between the AP y and its neighbors in order to try to meet the constraint (5) of the BLP problem (line: 5). If the prioritization of ISM band is considered (i.e. *Prior=True*) and the maximum P between the AP y using C_S and any of its neighbors is equal or lower than P_{MAX}, or the AP y has no available primary channels, then channel C_S is assigned to the AP y (line: 6), unless the AP y has available primary channels, then C_S is temporally saved as *Sch*, and 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 is going to 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: 13–15). Notice, as in constraint (4) 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.

5. Performance Evaluation

A performance analysis of the proposed algorithms is carried out in this section under different conditions of APs' density and primary spectrum heterogeneity. Two metrics to measure the achievement of the objectives of the formulated channel allocation problem are used for the algorithms' performance comparison. These are: a) the percentage of feasible assignments (FA) that each algorithm is able to satisfy under a number of random network topologies and b) the percentage of APs using PB channels. To that end, a number of topology snapshots are generated by randomly placing primary and secondary users on an area of 1 km × 1 km.

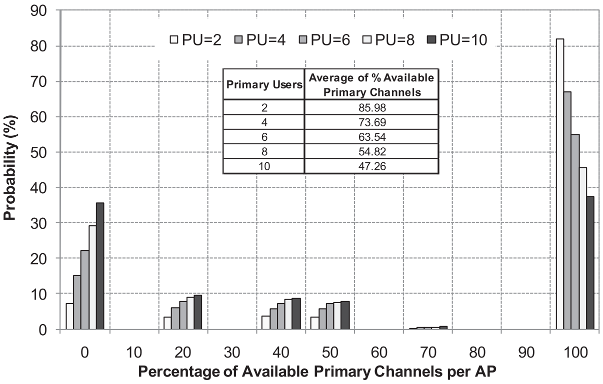
Table 1 Simulation parameters.

Parameters	Value
Protection margin of SU, M_S	10dB
Protection margin of PU, M_P	15dB
Sensitivity of SU, S_S	-65dBm
Sensitivity of PU, S_P	-65dBm
Propagation slope, α	3.5
Usage radius of SU, $R_{UA,SU}$	50m
Usage radius of PU, $R_{UA,PU}$	51m
Maximum interference radius from an SU to PU, $R_{IA,SU\to PU}$	18m
Maximum interference radius from an AP to another AP, $R_{IA,ap\to ap}$	14m
Maximum interference radius from a PU to the SU, $R_{IA,PU\to SU}$	10m
Maximum Interference 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

Notice that a feasible assignment means that the resulting channel assignment solution is able to guarantee that the P between each pair of APs is below the maximum allowed interference penalty (P_{MAX}). In this particular study, for the sake of simplicity, the spectrum masks for primary and WLAN transmissions are considered to have a rectangular shape, as shown in Fig. 1. 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, the same 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 22 MHz. Provided results have been obtained from 5000 snapshots. Simulation parameters are shown in Table 1.

5.1 PB Channel Availability Characterization

The availability of primary band channels that can be potentially used by APs in the scenario under analysis is illustrated in Fig. 6. Specifically, Fig. 6 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 only 2 primary users are considered, more than 82% of APs can use the 100% without impairing PU operation and only less than 10% of APs have no primary channel availability at all. On the other hand, if the number of primary users is set to 10, the percentage of APs with full primary band availability is reduced to below 40% and the percentage of channels available in each AP takes on different values (i.e. increase of the spectrum heterogeneity).

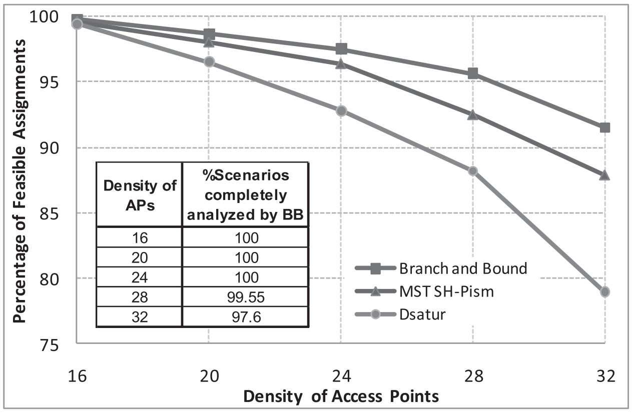


Primary Users	Average of % Available Primary Channels
2	85.98
4	73.69
6	63.54
8	54.82
10	47.26

Fig. 6 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.

5.2 Simulation Results

In this section, the proposed MST algorithm is evaluated and its performance compared to the optimal solution derived from the BLP formulation and to another solution, referred to as Dsatur, which is widely utilized by the research community [12] for solving the channel assignment problem in legacy WLANs. Dsatur, introduced by Brélaz [13], is based on the concept of a saturation degree. The saturation degree of a vertex is defined as the number of differently colored vertices to which the vertex is adjacent. These different colors used by the neighboring vertices then constitute a set of non-admissible colors for the vertex in question. The basic idea behind this algorithm is to choose the vertex with the highest saturation degree for each iteration and color it with the least admissible color. The MST algorithm is referred to as: "MST SH-Pism", in which SH and Pism refer to the fact that the algorithm is performed by considering spectrum heterogeneity and prioritization of ISM bands respectively. To solve the BLP problem, the BINTPROG function from the optimization toolbox provided by MATLAB is utilized. Function implementation is based on the Branch and Bound (BB) algorithm [18]. The BB algorithm creates a search tree in order to satisfy the constraints of the problem (i.e. (4) and (5)). If this condition is possible, then the scenario is feasible and the algorithm tries to minimize the number of APs using primary band (i.e. (3)). Otherwise, if constraints are not satisfied, the obtained assignation is unfeasible and is not optimized. On the other hand, for small scenarios (i.e. with few variables), the required computational time is acceptable; while for more complex scenarios, the computational efforts are substantially increased, so that the computational times and resources required by the algorithm to fully analyze the search tree are very high. Because of this, BINTPROG function has some configurable fields that limit the extensions of the search tree. In this study, the maximum amount of execution time of the algorithm is set to 21600 seconds, as a practical configuration to be used. In order to obtain a metric that allows the identification of the



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

Fig. 7 Percentage of feasible assignments for Branch and Bound, MST and Dsatur versus density of access points per unit area, for a density of 20 PUs.

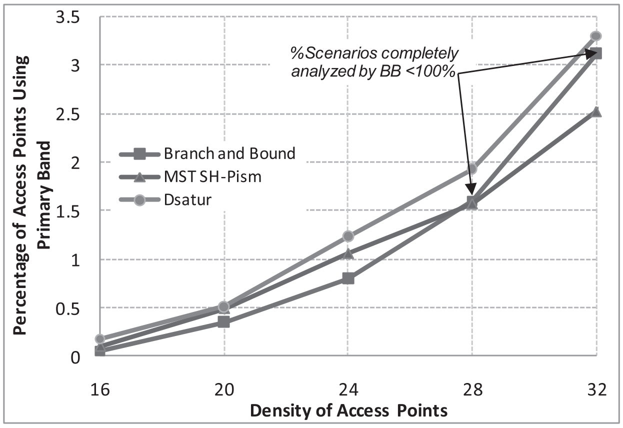


Fig. 8 Percentage of APs using primary band for Branch and Bound, MST and Dsatur versus density of access points per unit area, for a density of 20 PUs.

impact of these fields on the performance of the BB algorithm, Fig. 7 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 solutions optimized plus unfeasible brought by this algorithm. However, for densities larger than 28 APs, the BB algorithm is not always able to come up with a final solution (e.g. nearly 3% of analysed 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). Also, in Fig. 7, it is important to note that the MST results are closer to the BB than the Dsatur results. In Fig. 8, the percentage of APs using primary band required by MST is shown to always be lower than that required by Dsatur. This is the consequence of the fact that MST has the capability of prioritization of ISM band. So, for instance, for 32 APs, MST obtains around 10% more feasible assignments than Dsatur and requires around 0.8% less of APs using primary band. Since previous results have shown that MST is better than Dsatur, when both are compared to BB, the next results have been obtained only for MST and Dsatur. It is also interesting to note in Fig. 8 that the performance of BB for higher densities of APs is worse than that of MST due to the "bad" solutions given by BB when it is not able to conclude its operation.

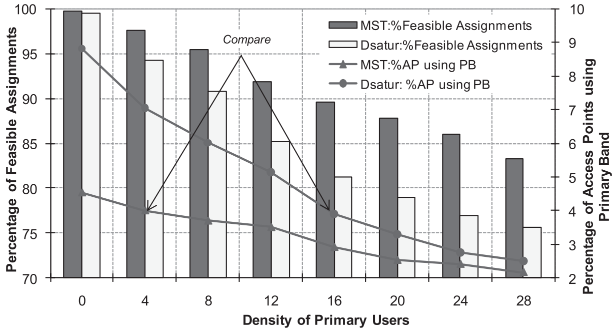


Fig. 9 Both percentage of feasible assignments and percentage of APs using primary band versus density of primary users per unit area, for a density of 32 APs.

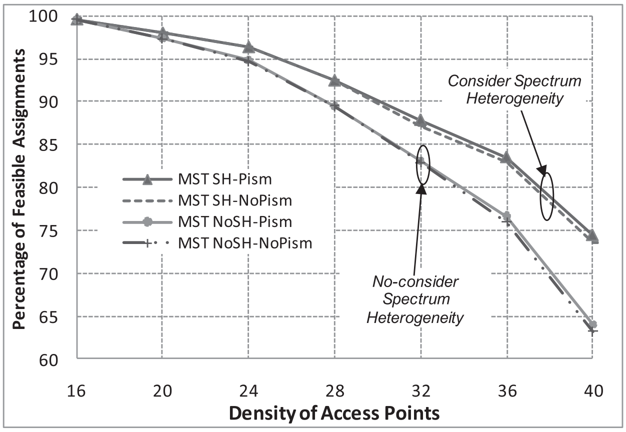


Fig. 10 Percentage of feasible assignments for variations of the MST versus density of access points per unit area, for a density of 20 PUs.

Figure 9 depicts the percentage of feasible assignments and the percentage of APs using primary band obtained when the spectrum heterogeneity increases (i.e. incrementing density of PUs). The figure illustrates that MST makes more efficient use of additional spectrum than Dsatur, because it finds more feasible scenarios and exposes the APs to much less possible changes in the primary band. For instance, for a density of PUs of 4, MST requires approximately the same percentage of APs using primary band (i.e. around 4 APs) than Dsatur for a density of 16 PUs, and provides around 17% more feasible scenarios.

Figure 10 provides the percentage of feasible assignments for different densities of APs within the scenario. As shown in the figure, when the spectrum heterogeneity is considered, the MST algorithm achieves more feasible assignments than if it is not considered. For instance, for 36 APs

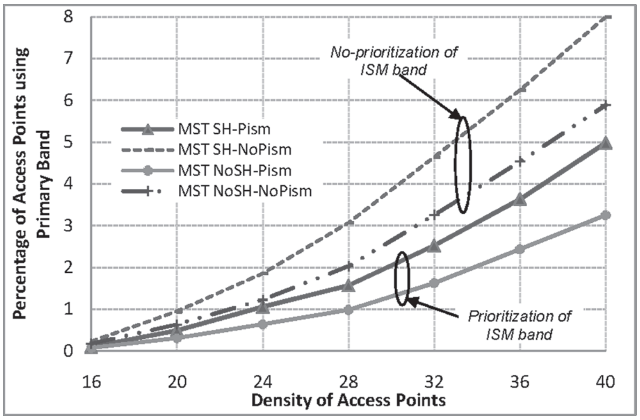


Fig. 11 Percentage of APs using primary band for variations of the MST versus density of access points per unit area, for a density of 20 PUs.

MST SH-,Pism finds around 8% more than 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 allocation process, i.e. MST SH-Pism.

Figure 11 shows the percentage of APs using primary band necessary for finding the feasible assignments of Fig. 10. This figure illustrates, as expected, that when the prioritization of ISM band is considered, the percentage of APs using primary band is always less than when it is not considered. For instance, for 36 APs, the percentage of APs using PB obtained by the algorithm MST SH-Pism is around 50% less than for MST SH-NoPism. Additionally, the amount of feasible assignments obtained by both considerations is similar. Furthermore, the prioritization of ISM band in the channel allocation 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.

6. Conclusions

This paper has proposed and evaluated the performance of a heuristic algorithm designed for opportunistic channel allocation in OSA-enabled WLANs. The channel allocation problem has been formulated as a BLP problem and the heuristic algorithm has been successfully proven to obtain a significant number of feasible assignments with highly reduced computation complexity when compared to time-consuming branch and bound algorithms. The algorithm is 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 algorithm has 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 as much as possible the channel allocation from the temporal and spatial variations of the primary channels' availability. Likewise, the proposed algorithm finds more feasible assignments when the heterogeneity of available primary channels increases. Moreover, since the proposed algorithm needs to receive information from all APs in order to build the MST, this one can be considered as a centralized solution.

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Francisco Novillo received the Engineer of Telecommunications degree, and a Master in Telecommunication Business Management from the Escuela Superior Politécnica del Litoral (ESPOL) in Guayaquil — Ecuador, and a Master in Mobile Communication from the Universitat Politècnica de Catalunya (UPC) in Barcelona — Spain, where he is currently developing his PhD in the Signal Theory and Communication Department. Since 2001, he is an Associate Professor of the Electrical and Computer Engineering Department at the ESPOL. The current topics of research are focused on radio resource managements, opportunistic spectrum access, and cognitive radio.

Ramon Ferrús received the Telecommunications Engineering (B.S. plus M.S.) and Ph.D. degrees from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1996 and 2000, respectively. He is currently Associate Professor with the Department of Signal Theory and Communications at UPC. His actual research interest is focused on architectures, QoS, mobility and radio and spectrum resource management in the context of heterogeneous wireless communications systems. He has participated in several research projects within the 6th and 7th Framework Programmes of the European Comission, as well as in research and technology transfer projects for private companies. He is co-author of one book on mobile communications and 60+ papers published in peer reviewed international journals, magazines and conference proceedings.