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Multivariable algorithm for dynamic channel selection in cognitive radio networks

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Abstract

The spectral handoff is important in cognitive wireless networks to ensure an adequate quality of service and performance for secondary user communications. This work presents a multivariable algorithm for dynamic channel selection used in cognitive wireless networks. The channel selection is based on the fuzzy analytical hierarchical process (FAHP) method. The selected criteria for choosing the best backup channel are probability of channel availability, estimated channel time availability, signal to noise plus interference ratio, and bandwidth. These criteria are determined by means of a customized Delphi Method and using the FAHP technique; the corresponding weight and significance is calculated for two applications classified as best effort (BE) and real time (RT). The insertion of the fuzzy logic in the AHP algorithm allows better handling of inaccurate information because, as shown the results, consider more options to evaluate in contrast to a conventional AHP. As a difference with related work, the performance of our proposed FAHP method was validated with captured data in experiments realized at the GSM frequency band (824–849 MHz). This is due to the challenge of finding white spaces to communicate in this frequency band. This band represents more disputes in accessing spectral opportunities than other radio frequency (RF) bands because of the high demand for mobile phone communications. The proposed FAHP algorithm has a practical computational complexity and provides an effective frequency-channel selection. This proposed FAHP algorithm presents a new methodology to select and classify the variables based on a modified version of the Delphi method. The results of the proposed method were contrasted numerically with other three methods.

Keywords: Backup-channel selection; Spectrum mobility; Cognitive radio; Decision making

1 Introduction

The inefficient and sporadic utilization of the spectrum, combined with the increased utilization of the radio frequency environment, have degraded the quality of service for various wireless networks and applications, for example, at the cellular network. This has motivated the development of new research in dynamic spectrum access (DSA) as a possible solution, particularly in cognitive radio (CR) [1–4]. According to the National Information Management and Communications (NTIA), the CR is a radio device capable of sensing the operational electromagnetic environment, adjusting dynamically and autonomously its radio-operating parameters to modify the system operation. In addition, it maximizes performance, reduces interference, and facilitates interoperability. The CR may provide high bandwidth (BW) to mobile users due to the DSA over several heterogeneous wireless architectures [5, 6]. This increases the spectral efficiency because it allows unlicensed users to opportunistically share the spectrum with licensed users [1].

The spectrum mobility also called spectrum handoff can be defined as the process where a secondary user (SU) or CR user changes its operating frequency when channel conditions are degraded, for instance, when a primary user (PU) arrives at the same frequency or when the SU is interfering with a PU [1]. The spectrum handoff is proactive when the need for a channel change is predicted in advance, and it is reactive when the device is waiting for the conditions to change the operating channel and hops to another frequency as quickly as possible. For a proactive handoff strategy, to have a

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backup channel (BKC) is necessary because it allows quick spectral handoff and delay reduction in order to improve the communication performance.

Our work presents a technique for the decision of the spectrum and, in particular, for the selection of a backup channel for spectral mobility, i.e., handoff strategies. BKC is a channel that has been previously selected based on rules and predefined criteria applied by means of the FAHP algorithm. This allows the SU to change channel with shorter delay because it is not necessary to wait until the spectrum detection or decision of spectrum is performed as mentioned in [1, 7, 8].

Multiple channel moves induced by a poor channel selection cause a significant increase in delay, which directly affects performance and QoS of secondary communications [9]. Transmissions may be paused when the selection of a channel is defective because it may change for various reasons, for instance, when the selected channel is about to be occupied by a PU, it is already occupied, or it presents low quality for transmissions. Hence, finding a channel suitable for communication is essential for spectral mobility [10]. Also, channel selection depends on several factors, for example, channel capacity, channel availability during the spectral handoff, and the probability of channel availability. Poor channel selection can cause multiple spectral handoffs, which may degrade performance of the whole system. The most common approach for channel selection is to employ a list of BKCs, e.g., in [10, 11]. The most common channel selection approach is to use a list of BKCs, i.e., as presented in [10, 11].

This work presents a multivariable algorithm for dynamic channel selection used in cognitive wireless networks based on the fuzzy analytical hierarchical process (FAHP) method. The criteria of probability of channel availability (AP), estimated channel time availability (ETA), the signal-to-interference-plus-noise ratio (SINR), and BW were selected by means of a customized Delphi method [12, 13]. This is in order to achieve the goal of selecting the best backup channel for specific requirements. The new methodology introduced in this work of a four-variable selection and the evaluation method by means of the inclusion of the fuzzy logic to the AHP is combined to achieve dynamic channel selection of the spectrum. In addition to the new methodology introduced in this work, one significant difference of our approach, when compared to related work in the literature, is that our proposed FAHP method is validated with experimental data captured from the GSM frequency band (824–849 MHz). For the evaluation of the data, our approach uses four variables to select the most suitable channel; while for the majority of the spectral handoff, algorithms use only one or two variables of information.

The rest of the manuscript is structured as follows. In Section II, a description of related work is presented. Section III describes the development of the FAHP algorithm. In Section IV, the results of the developed algorithm are shown. Finally, the conclusions are presented in Section V.

2 Related work

This section provides a description of recent work on algorithms for channel mobility in cognitive radio networks (CRN). The selection of the criteria is a fundamental task for proactive evaluation of the availability and optimal conditions for selecting a BKC. Once the selection criteria are established, the development of the multiple-criteria decision-making (MCDM) methodology is widely used as it is found in the literature. This MCDM method is based on two processes, the weights assessment of each criterion using the FAHP and the ranking estimation of each possible solution by means of one of the following techniques: the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Simple Additive Weighting (SAW), Multiplicative Exponential Weighting (MEW), or the Grey Relational Analysis (GRA) [14–19]. For instance, the authors in [20] proposed the decision making for spectrum selection by finding the shortest path of a tree-structure solution which meets certain required criteria for a class of service or application. In [20], a method is shown based on a modified version of the Dijkstra's algorithm, and the authors consider four parameters for the channel selection, quality of service, occupancy, SINR, and BW for the following two types of services: best effort (BE) and real time (RT). In addition, they also showed a new method for decision making, which consists in assigning vertices or edges to the spectrum representation according to the attributes or parameters to be evaluated. These edges create a matrix in order to obtain an adjacent list in graph's theory terms of computer science. The adjacent list size depends on the frequency bands available which are identified with a number from zero to n that represents a pre-allocation weight for each attribute or parameter, and hence, helping to identify the shortest path. The main advantage of the modified Dijkstra algorithm shown in [20], in contrast with the proposed FAHP, is response time, which is around a 1.5 % improvement considering 124 frequency channels analyzed. However, the Dijkstra algorithm presents 24 % more handoffs for a transmission of 4 min with respect to the FAHP. In addition, the FAHP algorithm uses fuzzy logic which allows managing vague information, and the validation results are nearer to the captured data than the validation of the Dijkstra algorithm. Thus, the FAHP results to being more advantageous than the Dijkstra algorithm.

The authors in [21] used a fuzzy logic method to create a table for channel reservation; thus, when a handoff takes place, the SU can quickly choose a frequency channel which is available to continue with the data transmission, and as a consequence, reduces the handoff latency. If the PU arrival is uncertain, the channel selected from the table may be occupied. However, this potential error is minimized by frequently updating the BKC table. The results achieved in this proposal show a reduction of the handoff delay and an increase in the effective rate of data transmission from the SU. The model used in [21] obtains shorter response times compared with the proposed FAHP; this is because it only uses two information variables, which are the occupation rate of the channel and the distance between the base-station and the SU. This approach is rather inaccurate. In contrast, the proposed FAHP algorithm offers high precision including four information variables; this contributes to having a reduced handoff-rate, and in addition, the FAHP optimizes performance for the BE and RT applications.

The authors in [22] proposed a channel allocation scheme for the IEEE 802.22 system which improves the performance of the probability of forced termination rates (FTR). This article focuses on the medium access control (MAC) layer that allows the coexistence between SUs and PUs and includes the following two elements: the spectrum label and the low on-demand frame contention (ODFC). The channel allocation scheme is developed based on the classification of operation, backup, and candidate channels. The parameters considered for the selection of the channels in this classification scheme are the interference and the arrival probability of PUs. The proposed scheme works as follows: if a PU arrives at the operating channel of the SU, the SU moves to the BKC and the candidate channel is used as the new BKC; if two PUs arrive, one at the operating channel and the other at the BKC, the candidate channel is immediately selected as the operating channel of the SU. The results show that FTR improves based on the interference measurements.

The main advantage of the algorithm presented in [22] is that it assesses a list of the three best channel options used to perform a spectral handoff considering the interference and the arrival probability of PUs. This is a widespread task for several spectral models. Nevertheless, the proposed FAHP not only selects the best three options but also arranges the channel options from best to worst for all frequency alternative channels in the analyzed bandwidth. The proposed FAHP uses four information variables rather than the two variables used by the algorithm presented in [22]. Additionally, the FAHP evaluates the alternatives with fuzzy logic to handle vague information using the captured data.

The authors in [11] proposed a protocol for MAC for CRN without a common control channel (CCC) named in [11] as CRUAM-MAC. This protocol has been validated using a discrete-event simulator to characterize the SUs' communication in the presence of PUs. The results show that the developed protocol causes minimal interference to PUs' transmission and also reduces the access time to the channel, as well as the packet lost compared to an overlay implementation of CSMA/CA for CRN. The CRUAM-MAC solution in [11] does not need a CCC for the communication among SUs, which is the main advantage. Nonetheless, the decision-making algorithm in FAHP offers a reduced number of handoffs compared to the CRUAM-MAC.

The authors in [23] propose dynamic channel-selection policies for CRNs in order to achieve efficient communication. Three types of methods for selecting channels are proposed as follows: the first is the weighted selection; the second is a sequential selection, and finally, a combined selection. The result is a protocol that provides an optimal channel list to be occupied. In spite of the selection methods, diversity shown in [23], and the use of five information variables for the decision making, this algorithm does not adjust the selection according to a particular application, for instance, BE or RT. Moreover, it lacks of the assessment of vague information as a substantial difference with respect to the proposed FAHP.

The authors in [24] propose a channel-selection algorithm considering the quality of service requirements of the CR users; this is based on measuring the channel utilization. The algorithm is flexible to achieve different degrees of compromise to establish a trade-off between the system data rate and users fairness. The simulation results show that the proposed algorithm can achieve up to a 30 % performance increase in the data rate, while ensuring a higher level of equality to a scheme in which the channel selection is random. The algorithm presented in [24] shows a trade-off between the data rate and the user's fairness. This balances the resources among SUs, but its decisions are limited to measurements of the occupation of the channel only. The proposed FAHP has four information variables, in addition to the fuzzy logic implemented for the decision making which improves accuracy.

The authors in [25] applied automata learning techniques to enable a CR to learn and make decisions on channel selection from a set of available channels. The random set of available frequency channels is modeled as an unknown environment. Due to practical networks being generally non-stationary, it proposed an adaptive algorithm that enables the CR to monitor the environment changes and to select the optimal channel after a long period of monitoring. The ability to operate in unknown environments and the adaptability of the automata technique presented in [25] are the strongest arguments; the main drawback is that it takes a long period of monitoring to obtain the optimum selections. Moreover, the computational complexity is significantly higher than the one required in the proposed FAHP.

The analytical hierarchical process (AHP) decision making based on the multiple criteria (MCDM) technique has proven to be an effective method for the selection of BKC alternatives [15, 16, 26–29]. Furthermore, if this is complemented with fuzzy logic (FAHP), it improves the management of subjectivity and reduces uncertainty in the information and also improves the criteria assessment, as proposed in our work which is presented in Section III.

3 Design of the proposed algorithm

3.1 Fuzzy analytical hierarchical process

The AHP method is an estimation algorithm for multi-criteria decision making including quantitative and qualitative criteria. The AHP problem can be divided in four hierarchical levels: objective, criteria, sub-criteria, and alternatives. The objective is the pursued goal in the decision-making algorithm. The criteria and sub-criteria are the factors affecting the preference of the alternatives. The alternatives are a set of possible frequency options to choose. This is based on subjective judgments, by contrasting the significance of the criteria used for the selection of diverse alternatives. As a consequence, this becomes a relative measure rather than an absolute assessment [30]. However, the AHP Saaty method [30] has some limitations such as: (1) it works with an unbalanced scale of judgments, (2) it cannot handle uncertainty and ambiguity in the information associated to the assigned number of each assessment, (3) the ranking of AHP is rather vague, and (4) the subjectivity of the judgment where the selection and preference of decision makers have significant influence on the results. These limitations can be mitigated by the integration of the fuzzy logic to the AHP algorithm, which results in the fuzzy analytic hierarchical process (FAHP) method [18, 31, 32].

The fuzzy logic is based on the theory of diffuse sets proposed by Zadeh [33]. A diffuse set is defined by a membership function that maps elements to grades of membership within a certain range, which is usually 0 or 1. If the value is 0, the element does not belong to the set; otherwise, if the value is 1, the element belongs completely to the set. If the value is an intermediate quantity, the element has a membership degree to the set [32]. The triangular fuzzy numbers (TFN) are widely used as membership functions because of its computational efficiency.

The TFN can be denoted as (l, m, u) where the parameters l, m, and u represent the lower limit, the modal number, and the upper limit, respectively, as shown in Fig. 1 and Eq. 1.

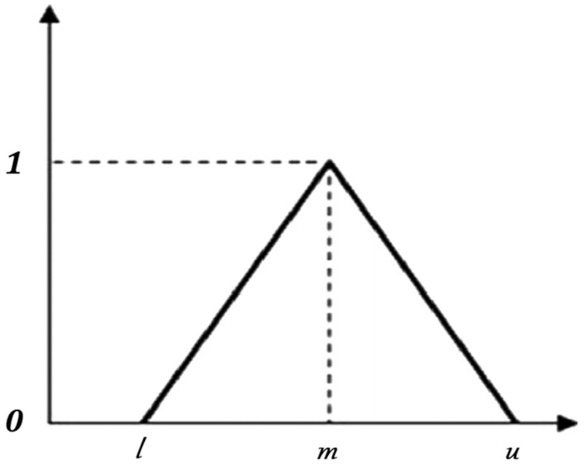

Fig. 1 Triangular fuzzy number [12]

$$\mu_A(x) = \left\{ \begin{array}{c} 0, x < 1, \\ (x-1)/(m-1), 1 \leq x \leq m, \\ (u-x)/(u-m), m \leq x \leq u, \\ 0, x < u, \end{array} \right\} \tag{1}$$

Fuzzy logic is an appropriate tool to make decisions in situations where the available inputs are uncertain and imprecise or qualitatively interpreted. Fuzzy logic can also transform qualitative and heterogeneous information in homogeneous membership values, which can be processed by a set of appropriate rules of fuzzy inference [34].

Although the FAHP method utilizes essentially the same methodology as the AHP algorithm, the fuzzy logic deals with the subjectivity and uncertainty in the criteria assessments, since the fuzzy logic, by means of a mathematical process, uses a range for the response instead of a precise number [35].

Recently, the FAHP algorithm has been widely used to solve multi-criteria decision-making problems in several fields [32] such as thermal plants generators [36], quality of service strategies [37], and energy planning [38]. Our work here shows that their contribution can be extended to the studies of CR. The proposed FAHP algorithm which is adapted to work for CR was developed with four steps: (1) problem definition, (2) construction of the hierarchy, (3) construction of the matrix of judgments, and (4) calculation of the normalized weights. These steps are described in the following section.

The four steps implemented for the proposed algorithm FAHP are described as follows.

3.2 Problem definition

The FAHP problem can be divided into four hierarchical levels: objective, criteria, sub-criteria, and alternatives. The objective is the selection of the best available BKC in a CRN with RT and BE applications. The procedure to determine the criteria and sub-criteria is performed by the customized Delphi method. The Delphi method is relatively simple and cheap to implement and has been adopted for diverse applications. It can be used for nearly any forecasting, estimation, or decision-making problem [13]. The method generally consists in a panel of experts answering questionnaires in two or more rounds. After each round, a facilitator provides an anonymous summary of the experts' forecasts from the previous round, as well as the reasons they provided for their judgments. In our proposed implementation, the input variables of the FAHP algorithm are defined by the parameters reported in the literature (those reported for cognitive devices), and the variables determined by the customization of the Delphi method. Thus, the CR device chooses the band that may be used for initial transmission according to active applications, e.g., BE or RT, using captured data, which means that the selected parameters are acquired by sensors or receiver devices. In addition, our implementation of the Delphi method includes rounds of experts' decisions. Our contribution to the Delphi process is the definition of the experts themselves. This means that experts are people involved in the administration or operation of the network, plus information obtained from the literature. Therefore, for the first round and for each selection round of the Delphi procedure, we consider two inputs: the decision of a board of administrators of the network, plus the variables high ranked in the literature. As a result of the first stage of the implemented Delphi method, 13 variables that affect the spectral handoff were selected by inspection of the related work reported in the literature, establishing the ranking of variables plus the opinion of nine operators of the network, i.e., a randomly selected board of administrators (BoA). Each analysis preformed using our method has to be adapted to the board's opinion plus the variables with high rank (VHR) reported in the literature. Then, the 13 selected VHRs for the beginning of the process are listed as follows.

*SU type of traffic: This parameter defines the characteristics of an information-cluster in communication, for example, video, audio, and data. For each type of traffic, there are different requirements, for example, for voice type of traffic in telephonic communication, the delay parameter is crucial.
*SU class of service: for the work presented, the case studies are RT and BE: It has been decided by the statistics of the VHR found in the literature to include the SU class of service for RT and BE as part of the AHP process because the service defines most of the characteristics of communication, for instance, delay and retransmissions.
*SU estimated transmission time: it is the average time that a SU occupies the frequencies assigned to the PUs. This parameter may help to assume a suitable frequency to be occupied by a SU.
*PU traffic pattern: this parameter describes the traffic behavior generated by the PU. The traffic pattern of the PU helps to model the use of the licensed spectrum, and thus, it may improve accuracy in predicting the availability of channels.
*SU traffic pattern: describes the traffic behavior of the SU, which is useful to describe the spectrum demand in case of several SUs trying to access the licensed frequencies.
*PU geo-location: represents the geographic location of the PU. This parameter is related to the behavior of the traffic for a specific location which is useful in predicting the spectrum occupancy.
*Signal-to-interference-plus-noise ratio (SINR): this is a significant parameter for energy detection because it comprises the ratio between the average power of the signal and the average noise power plus interference.
*Probability of channel availability (AP): it is the probability that a frequency portion, i.e., channel of the spectrum is available at the moment that a SU tries to access the medium. If the probability of channel availability is high, this indicates that the SU can occupy that channel, reducing the risk of interference to the PU.
*Estimated channel time availability (ETA): it represents the average time that a channel is available, this indicates to the SU which channels have high probability to allow longer communication without interruptions.
*SU transmission schedule: this parameter indicates the date of SU transmissions. The total load of the traffic varies according to certain schedule; thus, this parameter indicates a possible timetable for different traffic loads and the usability of the channels according to the date.
*Initial time of the SU transmission: indicates the time when a SU transmission starts. Similar to the SU transmission schedule, the initial time is important because the traffic load varies the day time, and it can provide information about the SU traffic load per hour.
*Bandwidth (BW): to know the bandwidth available is crucial for the spectrum decision and to determine the capacity of the channel for the SU and for the PU because it determines the range of frequencies that can be occupied by the SU in a particular instance.
*Bit error rate (BER): it is the number of received bits of a data stream over a communication channel that has been altered during transmission. This parameter

can help to evaluate a frequency band that presents a transmission with few errors.

The second stage of the Delphi method implemented considers the 13 VHRs selected during the first stage of the process in order to be presented to the BoA. The BoA determines which of the 13 variables are significant, or if variables should be added, modified, or discarded combined with the statistics of the VHR. This is known in the literature as the first round and corresponds to a statistical method where the variables that come out more often in the answers of the BoA are the ones to be selected for the first round. In case of disagreement among the BoA, a global analysis is performed combined again with the statistics of the VHR; after this, a second set of variables is proposed for a second round with the same procedure. This process repeats iteratively until a general consensus is reached by the board and combined with the statistics of the VHR. In our modified Delphi model, if the consensus does not take place before the fifth round, the final decision is taken based on the statistics of the final VHR, i.e., this considering only the statistics of the final selected set of VHR.

In the case-study of the proposed work, the consensus was achieved at the third round; at this stage, seven variables were discarded. The results showed that the type of traffic of the PU and SU were discarded because they can be characterized by the presence and absence of the PUs and SUs. Other VHRs discarded were the date and time of the transmission of the SU. This is because during the period of time of high demand of the spectrum, the “white spaces” are scarce, and it is not possible for the SU to find a frequency to allocate the communication. On the contrary, at the time when demand of spectrum resources is low, the allocations of SUs are straightforward without the need of using any decision criteria. Thus, the tests for our analysis are made at the time when demand of the spectrum resources is moderate. The geo-localization determines the spectral behavior directly, but for our analysis, it is considered in the data captured in a specific area, so this VHR was unnecessary. For the SU estimated transmission time, this variable can be estimated by the average time of a transmission, and due to this average number is a constant, it is not necessary to evaluate with the AHP algorithm; thus, it has been discarded by the rounds selection. The type of traffic parameter was discarded because it is directly related with the type of service. As a consequence, the type of service analyzed can be deduced by the application requirements in this work, BE and RT. Finally, the BER parameter was discarded because it can be estimated by the SINR; it then results as redundant for the AHP analysis.

After three rounds of the modified Delphi process, five variables were selected by the combination of the BoA decisions and the statistics of the VHR. These are SU class of service for the RT and the BE; signal-to-interference-plus-noise ratio (SINR), probability of channel availability (AP), estimated channel time availability (ETA), and bandwidth (BW).

The next step was to organize the criteria and the sub-criteria for the objective to find the best available channel for the SU. We considered that the class of service is more general than other variables, so we selected this as a decisive factor, classifying the criteria as: RT and BE and considering the other four selected variables as sub-criteria of the class of service. The criteria are determined by the application in our case, BE and RT. We consider that the goal is the same for BE and RT (the best available channel); however, the criteria to reach the goal are different. The objective is the decision making to be taken about the frequency channel, and so, for the current work, it corresponds to the selection of the best option for an available backup channel in the CRN with applications for RT and BE. The criteria and sub-criteria are the factors affecting the preference of the alternatives. The selection of weights is a collection of requirements of the parameters that characterized the RT and BE which results to being independent and different in weight in order to warranty these two applications. The variables were measured by experiments performed on different frequency channels. Then, the selected criteria were obtained using only experimental data.

It was decided to work with 124 frequency channels corresponding to the frequency band of 824 to 849 MHz of the GSM system mobile communication set ranging from the 128 to 251. The reason for choosing this set of frequency alternatives is based on the high demand for cellular telephony and the low quality of service presented.

3.3 Hierarchical structure and judgment matrices

The hierarchical structure is constructed based on the objective, the criteria, the sub-criteria and the alternatives. This is to develop the design methodology of the proposed FAHP algorithm, see Fig. 2.

Once the hierarchical structure is built, the judgment matrices are constructed according to the FAHP method. These matrices correspond to the comparative benchmarks that define the relative significance between possible combinations of pairs of criteria and sub-criteria. This work shows two criteria: RT and BE, which are mutually exclusive. Therefore, these two types of services are selected to be evaluated. This evaluation allows comparing the results with other studies that also selected the same criteria, for instance [11, 20, 26].

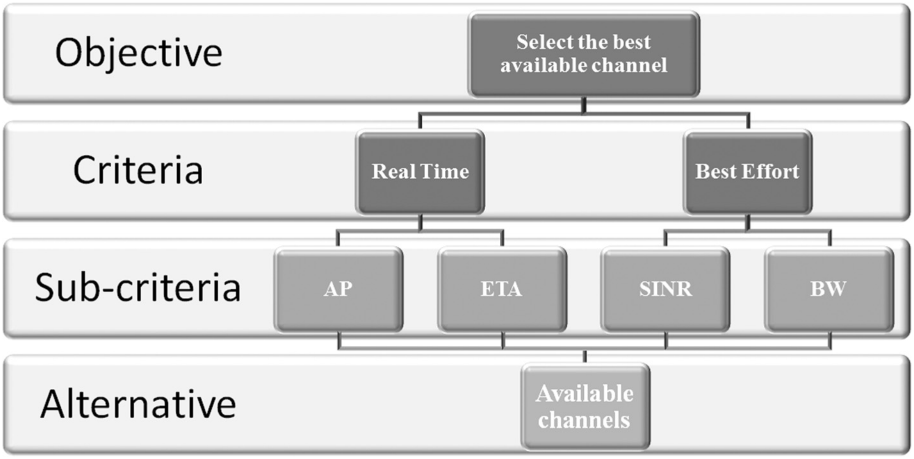

Fig. 2 Proposed FAHP hierarchy

For the analysis of the alternatives, it is considered that the frequency channels dynamically change their characteristics in time. Then, the FAHP algorithm dynamically evaluates the alternatives.

According to Büyüközkan [39], "those responsible for making decisions usually find that they feel better presenting their judgments as a range, instead of giving fixed values. This is because they are unable to explain their preferences, given the diffuse nature of the processes of human comparison", as a consequence, it was decided to work with a range of triangular fuzzy numbers, presented in Table 1 and Fig. 3. The fuzzy importance scale is obtained by the conversion of nine levels of the fundamental importance scale, to a fuzzy number presented by Büyüközkan [39].

Based on the fuzzy importance scale presented in Table 1 and Fig. 3 and using the customized Delphi method, the level of relative significance of each pair of sub-criteria was determined, and the judgment matrix for the sub-criteria with a RT approach was constructed, as seen in Table 2. The matrix for the BE approach can be seen in Table 3.

The preliminary matrix of judgments is built from the results of the first round of the customized Delphi Method as explained previously. The result of the first round is used in the second round for the BE and for the RT approaches. At the second round the values are decided and why. The decision process repeats until the results converge which represents the matrix of judgments shown in Tables 2 and 3.

The RT and BE applications have different approaches; therefore, for the RT process, the criteria with the highest priority are the ones that reduce delay, for instance, the AP and the ETA parameters. However, for the BE, the criteria that increase the data rate have the highest priority, for example, the BW and the SINR.

A matrix of judgments of "*n*" criteria or sub-criteria is described by Eq. 2,

$$A = [a_{ij}]_{nxn} = \begin{bmatrix} a_{11}a_{12}\ldots a_{1n} \\ a_{21}a_{22}\cdots a_{2n} \\ \vdots\ddots\vdots \\ a_{n1}a_{n2}\cdots a_{nn} \end{bmatrix} \tag{2}$$

where $i = j = 1, 2, \ldots, n$, and n is the number of attributes.

For the case of the FAHP algorithm, the judgment matrices contain the triangular fuzzy numbers which represent the pair comparisons between sub-criteria [31], as described by Eq. 3:

Table 1 TFNs and reciprocal TFNs for FAHP scale of importance [31, 39]

Nomenclature	Importance scale	Fuzzy triangular scale	Fuzzy triangular scale reciprocal
EI	Equal importance	(1/2, 1, 3/2)	(2/3, 1, 2)
MI	Moderate importance	(1, 3/2, 2)	(1/2, 2/3, 1)
SI	Strong importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
VSI	Very strong importance	(2, 5/2, 3)	(1/3, 2/5, 1/2)
XI	Extreme importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

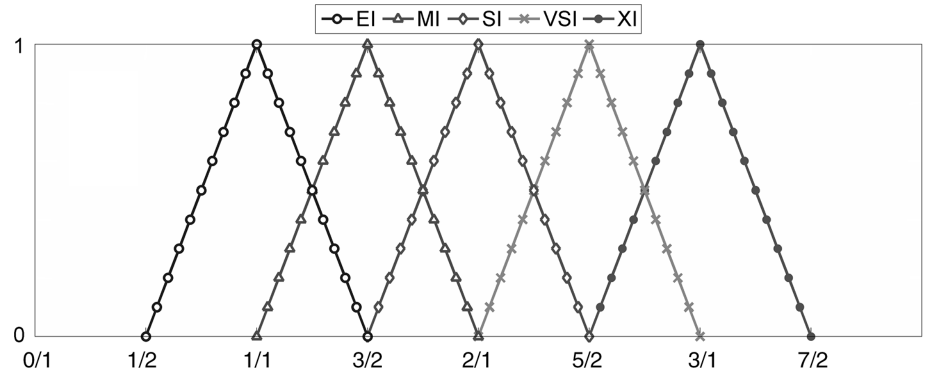

Fig. 3 TFNs for FAHP scale of importance

$$\tilde{A}\,(\tilde{a_{ij}})_{nxn} = \begin{bmatrix} (0.5,1,1.5)(l_{12},m_{12},u_{12})\cdots(l_{1n},m_{1n},u_{1n}) \\ (l_{21},m_{21},u_{21})(0.5,1,1.5)\cdots(l_{2n},m_{2n},u_{2n}) \\ \vdots\ddots\vdots \\ (l_{n1},m_{n1},u_{n1})(l_{n2},m_{n2},u_{n2})\cdots(0.5,1,1.5) \end{bmatrix} \tag{3}$$

Where $\left(\tilde{\tilde{a}}_{ij}\right) = \left[\tilde{\tilde{a}}_{ij}\right]^{-1} = \left(l_{ij}, m_{ij}, u_{ij}\right)^{-1} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right)$

For the proposed the FAHP algorithm, the judgment matrices obtained are described in Table 2 for the RT criteria and in Table 3 for the BE criteria. The diagonal of each matrix corresponds to the equality because it compares the importance of the sub-criteria with themselves. The upper half of the diagonal of the matrix describes the relative importance of the sub-criterion of the first column with respect to the sub-criterion of the first row.

The frequency channels (the alternatives) were evaluated dynamically using the actual values of the AP, ETA, SINR, and BW over the time for the RT and BE. This means that the alternatives are evaluated at the time of the algorithm execution.

3.4 Calculation of the normalized weights

With the judgment matrices already defined, the normalized weights were calculated for each sub-criterion based on the model proposed in [31]. These results are based on the fuzzy extended analysis presented in [40], as described as follows.

The i-th value of the extended analysis object is defined as shown in Eq. 4:

$$\tilde{\tilde{S}}_i = \sum_{j=1}^{n} \tilde{\tilde{a}}_{ij} \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{\tilde{a}}_{ij} \right]^{-1} \tag{4}$$

where,

$$\sum\nolimits_{j=1}^{n} \tilde{\tilde{a}}_{ij} = \left(\sum\nolimits_{j=1}^{n} l_{ij}, \sum\nolimits_{j=1}^{n} m_{ij}, \sum\nolimits_{j=1}^{n} u_{ij} \right)$$

and the inverse matrix of Eq. 4 is calculated from Eq. 5,

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{n} \tilde{\tilde{a}}_{ij} \right]^{-1} = \left(\frac{1}{\sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} u_{ij}}, \frac{1}{\sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} m_{ij}}, \times \frac{1}{\sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} l_{ij}} \right) \tag{5}$$

Table 2 Judgment matrix for the sub-criteria of the RT criteria

Sub-criteria	AP	ETA	SINR	BW
AP	(1/2, 1 ,3/2) EI	(1, 3/2 ,2) MI	(3/2 ,2, 5/2) SI	(3/2, 2, 5/2) SI
ETA	(1/2, 2/3 ,1) 1/MI	(1/2, 1, 3/2) EI	(3/2, 2, 5/2) SI	(3/2, 2, 5/2) SI
SINR	(2/5, 1/2, 2/3) 1/SI	(2/5, 1/2, 2/3) 1/SI	(1/2, 1, 3/2) EI	(1, 3/2 ,2) MI
BW	(2/5, 1/2, 2/3) 1/SI	(2/5, 1/2 ,2/3) 1/SI	(1/2, 2/3 ,1) 1/MI	(1/2, 1, 3/2) EI

Table 3 Judgment matrix for the sub-criteria of the BE criteria

Sub-criteria	AP	ETA	SINR	BW
AP	(1/2 ,1 ,3/2) EI	(1, 3/2, 2) MI	(1/3, 2/5, 1/2) 1/VSI	(1/3, 2/5, 1/2) 1/VSI
ETA	(1/2, 2/3 ,1) 1/MI	(1/2, 1, 3/2) EI	(2/5, 1/2, 2/3) 1/SI	(2/5, 1/2, 2/3) 1/SI
SINR	(2, 5/2 ,3) VSI	(3/2, 2, 5/2) SI	(1/2, 1, 3/2) EI	(3/2, 2, 5/2) SI
BW	(2, 5/2, 3) VSI	(3/2, 2, 5/2) SI	(2/5, 1/2, 2/3) 1/SI	(1/2, 1, 3/2) EI

The "possibility degree" for a convex fuzzy number to be greater than k convex, fuzzy numbers are given in Eqs. 6 and 7,

$$V\left(\tilde{S} \geq \tilde{S}_i\right) = V\left[\left(\tilde{S} \geq \tilde{S}_1\right) \wedge \left(\tilde{S} \geq \tilde{S}_2\right) \ldots \left(\tilde{S} \geq \tilde{S}_k\right)\right] \tag{6}$$

$$V\left(\tilde{S} \geq \tilde{S}_i\right) = \min\left\{V\left(\tilde{S} \geq \tilde{S}_i\right)\right\} \tag{7}$$

Wherein the possibility degree that $\tilde{S}_1 \geq \tilde{S}_2$ y $\tilde{S}_2 \geq \tilde{S}_1$ is given in Eqs. 8 and 9, respectively,

$$V(\widetilde{S_1} \geq \widetilde{S_2}) = \begin{cases} 1, m_1 \geq m_2 \\ 0, l_2 \geq u_1 \\ \dfrac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, \text{otherwise} \end{cases} \} \tag{8}$$

$$V(\widetilde{S_2} \geq \widetilde{S_1}) = \begin{cases} 1, m_2 \geq m_1 \\ 0, l_1 \geq u_2 \\ \dfrac{l_2 - u_1}{(m_2 - u_2) - (m_1 - l_1)}, \text{otherwise} \end{cases} \} \tag{9}$$

Now, assuming that $d_1' = \min\left\{V\left(\tilde{S}_1 \geq \tilde{S}_2\right)\right\}$, the weight vector is $w' = \left(d_1', d_2', \ldots, d_n'\right)$.

Finally, after normalization, the vector of non-fuzzy weights is given in Eq. 10,

$$\begin{aligned} W &= (d_1, d_2, \ldots, d_n)^T \\ &= \left(\frac{d_1'}{\sum_{i=1}^{n} d_i'}, \frac{d_2'}{\sum_{i=1}^{n} d_i'}, \ldots, \frac{d_n'}{\sum_{i=1}^{n} d_i'}\right) \end{aligned} \tag{10}$$

From the above procedure, the results from the weight vectors corresponding to the RT criterion are shown in Table 4, while the criterion corresponding to the BE are shown in Table 5.

The normalized weights describe the relative degree of importance of each sub-criterion for selecting the BKC for the RT and the BE criteria. For example, in case that a SU requires a BKC for the RT application, the channel selection weights depend on approximately 36 % for the AP, 30 % for the ETA, 20 % for the SINR, and 14 % for the BW. For the case scenario of the RT application, the AP and ETA are important because they allow selection of a frequency channel with a low probability of multiple handoffs. On the contrary, for the BE application, the sub-criteria SINR and BW are significant because they allow selection of a frequency channel with a practical channel capacity but without emphasizing on the delay during transmission.

Table 4 Normalized weights of the RT sub-criteria

RT sub-criteria	AP	ETA	SINR	BW
Normalized weights	0.3593	0.2966	0.1970	0.1471

Table 5 Normalized weights of the BE sub-criteria

BE sub-criteria	AP	ETA	SINR	BW
Normalized weights	0.1607	0.1523	0.3949	0.2921

With the weights shown in Tables 4 and 5, all available frequency channels are evaluated, which corresponds to the alternatives in the hierarchy of the developed FAHP algorithm. The channels are classified from the highest to the lowest evaluated scores and, with BKC resulting as the highest channel score.

4 Results

The evaluation and validation of the developed FAHP algorithm was performed using real experimental data of the spectrum occupancy measured in Bogota City, Colombia. This is in order to accurately assess the performance of the algorithm and validate the algorithm performance with applicable experimental data.

The first part of this section describes the process of capturing and analyzing the information of the spectrum occupancy. The second part, describes the results achieved in the evaluation and validation processes of the developed algorithm.

4.1 Information and analysis of the spectrum occupancy

This section describes the results achieved in the capturing process and also the analysis of the spectrum occupancy information. The setup of the equipment used for the capturing process is shown in Fig. 4. The equipment specifications are shown in Table 6. The technical parameter configured for the spectrum analyzer can be seen in Table 7.

To determine whether a frequency channel is busy or not, a decision threshold is determined based on the average noise floor for the frequency band used. We consider the specifications of the GSM band, the standard configuration of the spectrum analyzer, and the measurements to establish the noise floor and the guard level. The average noise floor is obtained by the spectrum analyzer measurements. The guard level was fixed at +5 dBm above the noise floor in order to minimize false alarms. However, the results obtained by the FAHP method are dependant on the criteria selected from the captured data, and the result varies according to the application requirements, for example, RT and BE. Therefore, the general performance of the proposed algorithm is independent of the selected threshold of the noise floor and guard band.

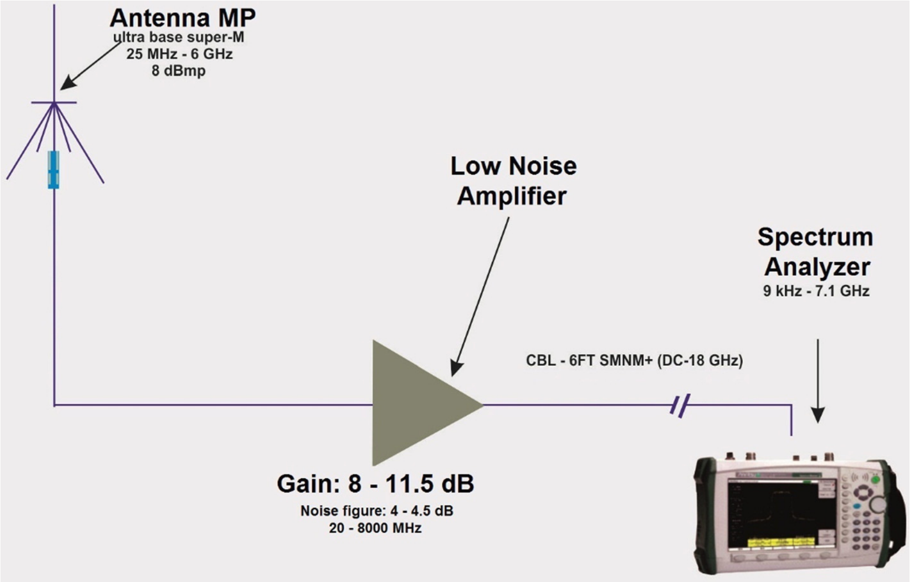

Fig. 4 Experiment setup to capture the data from the spectrum

The average value of the noise floor and the decision threshold are shown in Table 8.

The used spectrum analyzer was configured with a period of 333 ms for the sweep time; then, there are three sweeps per second for the frequency range of the selected band. The spectrum analyzer configuration for the Span and the RBW parameters allows performing 250 samples per sweep of the 25 MHz bandwidth from the 824 to 849 MHz. This frequency band corresponds to the uplink of the GMS band, and using uniform sampling over the 25 MHz of the GSM band, each sample represents a segment of 100 kHz, i.e., the 25 MHz divided by the 250 samples is the segment size of 100 kHz. The data is captured for 1 h; then, the amount of obtained data is 2,700,000 = 250 (data / sweep) × 3 (sweep/second) × 3600 (s). From these 2,700,000 data, a particular 4-min segment was selected because it corresponds to the frequency segment with the highest spectral occupancy, and this segment corresponds to 180,000 captured data, i.e., 2,700,000 data during 4 (min), divided by 60 (s), equal to 180,000 captured data.

There are 124 frequency channels for the uplink GSM band, each with a 200 kHz of bandwidth plus a guard band of 200 kHz, resulting in a 25-MHz bandwidth. For each sweep of the spectrum analyzer, two samples are captured per channel. The average of these two samples provides a single value per channel which results in 89,280 spectral data, i.e., 124 channels per 240 (s) per 3 (sweeps per second) equal to the 89,280 captured data.

These 89,280 data were organized and preprocessed to obtain the corresponding values of the sub-criteria per channel. Once spectral occupation data is captured, a pre-processing of the data is performed; this is in order

Table 6 The equipment specifications for the spectral measurements

Equipment	Specifications	
	Frequency range	Model reference
Discone antenna	25 MHz–6 GHz	Super-M Ultra Base
Broadband cable	DC–18 GHz	CBL-6FT SMNM+
Low noise amplifier	20 MHz–8 GHz	ZX60-8008E-S+
Spectrum analyzer	9 KHz–7.1 GHz	MS2721B Anritsu

Table 7 Technical parameters captured for the spectral occupation

Parameters	Value
Frequency band	824 to 849 MHz
Communication system	Mobile
Communication technology	GSM
Channels numbers	124 (128 … 251)
Detection technique	Energy detection
Capturing time	1 h
Number of selected samples	89,280 = 4 min
Sweep time	333 ms aprox.
Resolution BW (RBW)	100 kHz
Span	50 MHz

Table 8 Noise floor and decision threshold

Characteristics	Value (dBm)
Average noise floor	−113
Decision threshold	−113 + 5 = −108

to calculate the values of each of the determined sub-criteria in the hierarchy. Then, the different traces of spectrum occupancy obtained by the spectrum analyzer are unified. This encompasses a comprehensive database for the calculations in the evaluation process of the developed FAHP algorithm.

Table 9 shows the first 10 channels of the 124-channel uplink sub-band GSM in the database with the selected sub-criteria in the designed FAHP algorithm. It is important to remark that the calculations were assessed with 124 channels, but only the first 10 are shown for illustrative proposes.

The AP variable corresponds to the analysis of the duty cycle of the 124 frequency channels. Regarding the ETA parameter; the time is assessed considering the time that each channel was continuously available, and then, the average time is calculated. The SINR is calculated from the average of the difference between the power signal and the average floor noise. Finally, the BW is set to 200 kHz because that is the BW of each of the GSM channels. As a consequence, the BW parameter has no impact for the calculations of the frequency channel ranking. However, it is decided to leave it in order to characterize a general model.

Each analyzed channel obtains a score by using the weights assessed and shown in the Tables 4 and 5 for RT and BE, respectively, this is in addition to the absolute values of each sub-criteria, see Table 9. The channel score is calculated using Eq. 11 for the RT approach and Eq. 12 for the BE. The channel with the highest score is selected for the spectral handoff.

$$\begin{aligned} Puntaje\_canal\_i = 0.3593 \times AP_i + 0.2966 \\ \times ETA_i + 0.1970 \times SINR_i \\ + 0.1471 \times BW_i \end{aligned} \tag{11}$$

$$\begin{aligned} Puntaje\_canal\_i = 0.1607 \times AP_i + 0.1523 \\ \times ETA_i + 0.3949 \times SINR_i \\ + 0.2921 \times BW_i \end{aligned} \tag{12}$$

In order to maintain fairness between the score of the channels for BE and RT, all the values shown in Table 9 are normalized considering the same scale range from 0 to 100. This avoids significant differences between values of the sub-criteria. The normalization of the sub-criteria considered as the highest value (HV) of each sub-criteria is 100, and the rest of the values are assessed by multiplying per a scaling factor equal to the value per 100 divided by the HV.

For the BW sub-criteria, the scaling factor is 0.5, thus resulting in a 100 kHz of BW. The normalized sub-criteria of ten channels of the GSM band are assessed for a single instant of time and shown in Table 10.

The data captured and processed, which corresponds to the 124 channels, was analyzed, and the results are shown in four graphs: (1) spectrum occupancy of the frequency bands between 824 and 873 MHz, see Fig. 5; (2) the AP of each channel, see Fig. 6; (3) the ETA of each channel, see Fig. 7; and (4) the estimated SINR of each channel, see Fig. 8. For each graph, the sub-criteria values are calculated per channel, and then, the arithmetic mean of all of them are computed.

Figure 5 describes the spectrum occupancy of the normalized duty cycle for a segment of the GSM band. The duty cycle is the fraction of time that the channel remains occupied by the primary network [41].

It can be inferred from Fig. 5 that the GSM uplink at frequencies ranging from 824 to 849 MHz shows a duty

Table 9 Database for the sub-criteria of the first ten GSM channels, with BW of 200 kHz

Channel	Frequency (MHz)	AP (%)	ETA (s)	SINR (dBm)
1/128	824.20	96.58	8.37	2.30
2/129	824.40	93.59	4.56	2.35
3/130	824.60	94.01	4.88	5.44
4/131	824.80	97.43	10.85	1.45
5/132	825.00	91.45	3.96	9.05
6/133	825.20	94.87	5.69	4.72
7/134	825.40	93.59	4.86	6.03
8/135	825.60	89.31	3.16	8.08
9/136	825.80	97.43	10.85	7.56
10/137	826.00	97.00	9.45	2.13

Table 10 Database for the normalized sub-criteria of the first ten GSM channels, with a normalized BW of 100 kHz

Channel	Frequency (MHz)	AP (%)	ETA (s)	SINR (dBm)
1/128	824.20	96.58	21.55	24.08
2/129	824.40	93.59	11.75	24.52
3/130	824.60	94.02	12.59	56.81
4/131	824.80	97.44	27.96	15.16
5/132	825.00	91.45	10.21	94.43
6/133	825.20	94.87	14.66	49.34
7/134	825.40	93.59	12.53	62.95
8/135	825.60	89.32	8.15	84.36
9/136	825.80	97.44	27.96	78.95
10/137	826.00	97.01	24.36	22.31

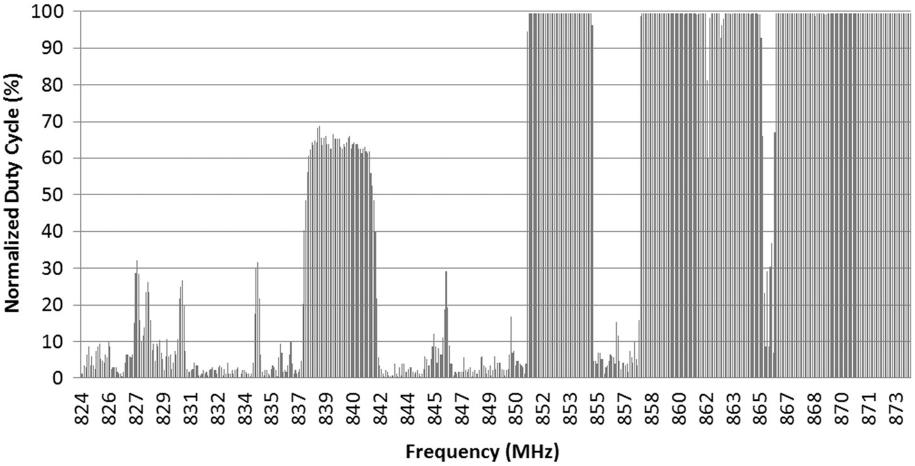

Fig. 5 Normalized duty cycle for the segment of the GSM band

cycle less than 25 %, while the remaining portion with frequencies ranging from 850 to 873 MHz corresponding to the GSM downlink shows a duty cycle greater than 75 %. This implies that the GSM downlink has a higher occupancy with three-quarters of the spectrum occupancy.

Figure 6 depicts the estimated AP per channel, where it can be observed that most of the channels have availability over 90 %.

Figure 7 depicts the ETA per channel. The contribution of this variable cannot be replaced by the AP variable. This is because when both variables are compared, see Figs. 6 and 7, it can be seen that although these two are correlated, their variations are different. While the former indicates the probability of finding the channel idle, the second estimates for how long the channel may stay idle.

Figure 8 describes the SINR for each channel, and it can be appreciated that a portion of the spectrum presents low SINR, which represents spectral opportunities. An inverse proportion between the SINR and the estimated availability time in each channel can be also observed.

4.2 Evaluation and validation of the FAHP algorithm

In this section, the performance of developed FAHP algorithm is evaluated from: (1) the level of accuracy in selection of the best BKC for the both criteria, RT and for the BE, (2) computational cost with respect to the analysis of the 1 to 124 alternative channels, and (3) the handoff-rate analysis with respect to the transmission time for the SU.

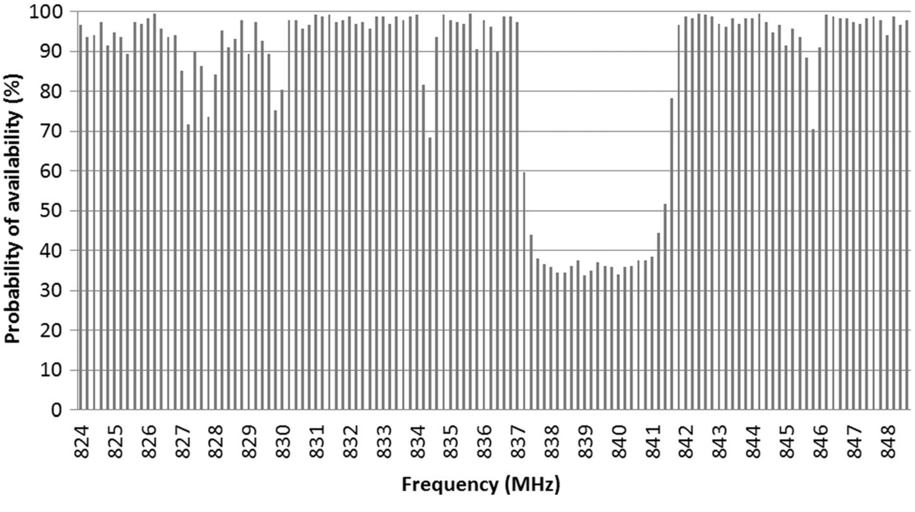

Fig. 6 Estimated AP per channel

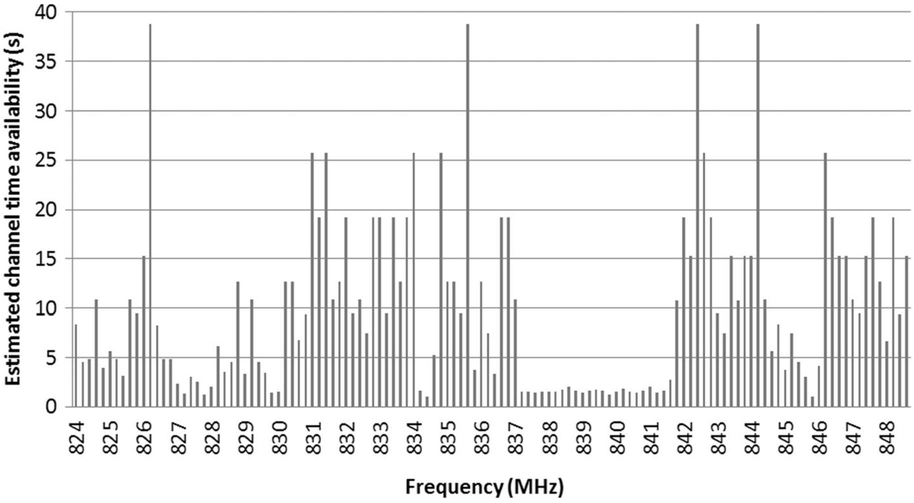

Fig. 7 ETA per channel

4.2.1 Accuracy analysis for the selection of the best channel backup

The accuracy analysis of the developed FAHP algorithm comprises four experiments: (1) for RT criterion, the status of availability per channel (SAC) is known, (2) for RT criterion, where the availability average value per channel (AAC) is only known, (3) for the BE criterion, where the SAC is known, and (4) for the BE criterion, where the AAC is only known. The SAC assumes for the spectral handoff that a measurement has been previously made to know whether the channel is available or not with certain precision, while the AAC predicts availability based on the average value per channel of previous availabilities.

For each experiment, 30 tests of channel selection were performed with data of the two following minutes to the 4 min of the captured data. These 2 min for each of the 30 tests are to validate the results. The 30 tests evaluate which percentage of the selected channels, indeed, corresponds to the available frequency channel in that particular instant. The results of the precision tests were compared per channel for the following algorithms, FAHP, AHP [26], the modified Dijkstra algorithm [20], and CRUAM-MAC [11]. The results are shown in Table 11.

For experiments 1 and 3, the instant values of each sub-criteria were utilized, and the results show that a high computational cost is required for the mobile

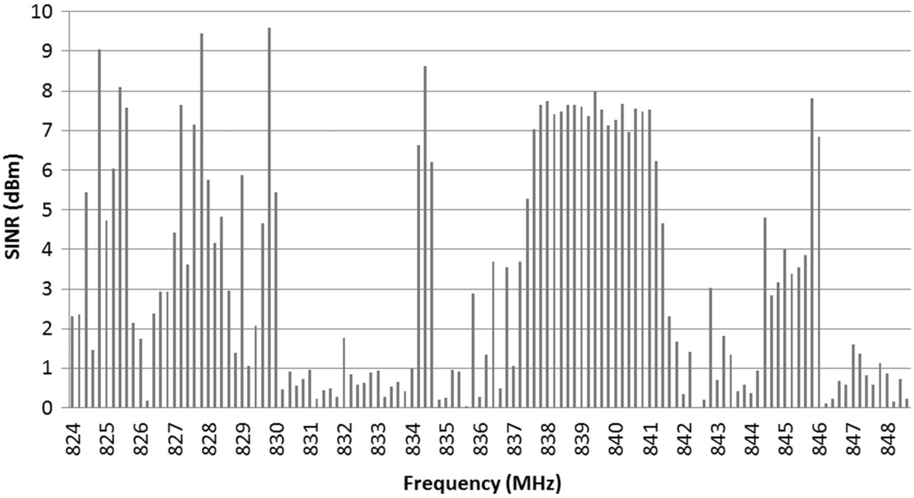

Fig. 8 Estimated SINR for each channel

Table 11 Accuracy analysis for the BKC selection

Algorithm	Criterion	SAC known	AAC known
Proposed FAHP	RT	100 %	95 %
	BE	100 %	85 %
AHP [26]	RT	100 %	93 %
	BE	97 %	83 %
Modified Dijkstra algorithm [20]	RT	100 %	76 %
	BE	93 %	70 %
CRUAM-MAC [11]	RT	100 %	NA
	BE	100 %	NA

device. It is also shown that the energy consumption increases as well as the channel move delay. In order to evaluate a practical case scenario, experiments 2 and 4 were performed; for these experiments, the average values of each sub-criteria are known and where the average values are periodically assessed.

It can be concluded by observing Table 11 that if the availability status is known of each channel in RT and BE, the developed algorithm performs with absolute precision in selecting the channel backup. However, if the calculation relies on an estimated value exclusively, the algorithm reduces their accuracy to 95 % for the RT and 85 % for the BE criteria. The CRUAM-MAC [11] selects the available channel based on the detection; as a consequence, this algorithm does the handoff with previous monitoring and for this reason, the handoff delay increases considerably. The proposed FAHP and AHP [26] manage a similar precision for the frequency channel selection. However, the proposed FAHP is slightly advantageous due to the fuzzy logic implemented and significantly improved with respect to the modified Dijkstra algorithm.

4.2.2 Analysis of the computational cost with respect to the channel alternatives

To perform this analysis, the delay of the developed FAHP algorithm execution was plotted based on the number of alternatives. This is in order to assess the computational costs of the algorithm for multiple alternatives of available BKCs and assessing when gradually the number of alternatives in the database increases. The results which show that the algorithm takes approximately 14 ms to evaluate the 124 channels can be seen in Fig. 9. This is a promising result for practical purposes; in fact, the FAHP algorithm's delay is 16 ms, which is less than the AHP algorithm delay presented in [26]. This comparison was performed over the same software and hardware conditions.

Using exhaustive regression analysis over the captured data shown in Fig. 9, it is observed that the linear and polynomial trends are the ones that better fit with the statistical data. The correlation coefficient is higher for the polynomial approximation than for the linear trend of data which are 0.994 and 0.947, respectively [42]. The difference between two coefficients is not significant, so we consider that the linear approximation is precise enough to estimate the convergence time of the FAPH algorithm for the number of spectral opportunities to be evaluated.

The proposed FAHP is compared in terms of computational cost with three algorithms, AHP [26], the modified Dijkstra algorithm [20], and CRUAM-MAC [11]. The comparative analysis of the algorithms is based on the alternatives using the same hardware and software, thus resulting in the proposed FAHP

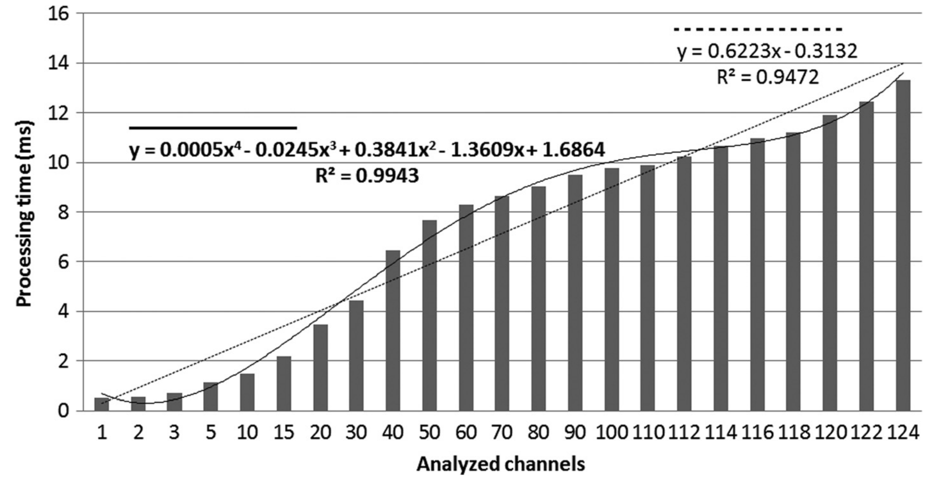

Fig. 9 Computational cost analysis with respect to the number of alternatives

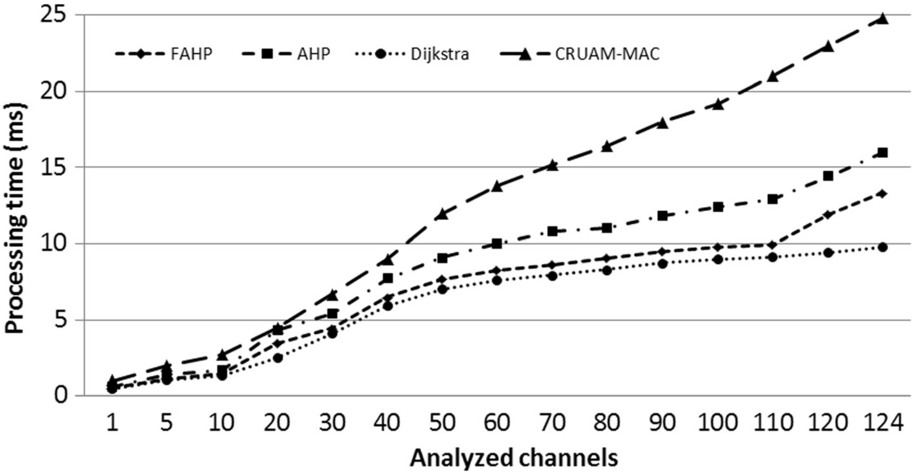

Fig. 10 Comparison of the computational cost with respect to the number of alternatives

with 11 % more computational cost than modified Dijsktra algorithm. But, FAHP improved with 76 % less computational cost than CRUAM-MAC and 22 % less than AHP as shown in Fig. 10. Then, we conclude from this that the use of FAHP for practical applications is feasible.

4.2.3 Analysis of the handoff rate versus transmission time of the SU

The handoff rate versus transmission time of the SU is plotted and analyzed. The transmission time was taken as a discrete (integer) and uniform variable between 1 and 15, called *n*, where *n* is measured in steps of 16 s, for a total of 15 values. The handoff rate is measured based on the channel moves required to complete the transmission time of the SU, initially for 16 s and then for 32 s and so on until a measurement of 240 s. Figure 11 shows the results obtained with the developed FAHP algorithm.

Despite the fact that there are few studies that have shown results of handoff spectral rates, Fig. 12 illustrates the comparison of the handoff spectral rate between the proposed FAHP and three more algorithms, CRUAM-MAC [11], AHP [26], and the Dijkstra algorithm [20]. The developed FAHP shows a considerable advantage of four times with respect to CRUAM-MAC, while it shows an advantage of 0.73 and 0.4 times with respect to the modified Dijkstra algorithm and the AHP, respectively. Thus, the proposed FAHP reduces the handoff spectral rate if compared with the other three algorithms. From

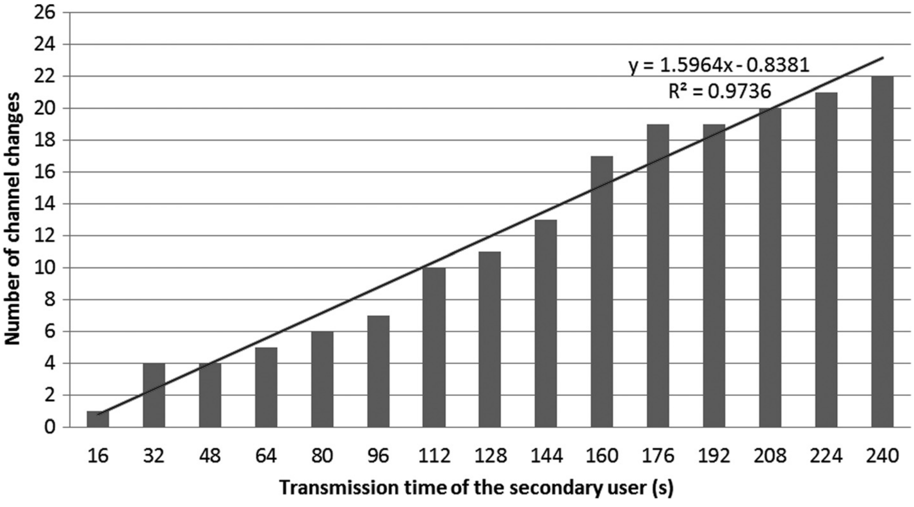

Fig. 11 Channel moves versus transmission time analysis

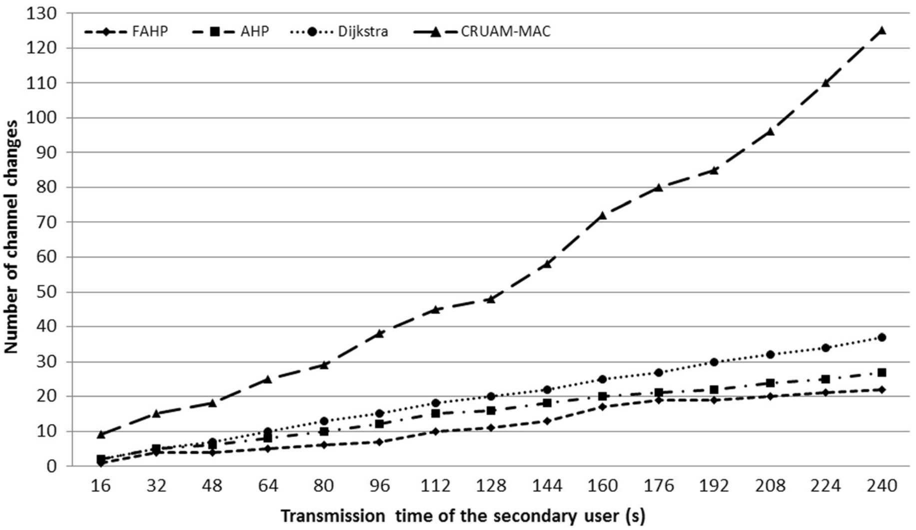

Fig. 12 Comparison between three algorithms and the proposed FAHP for handoff spectral rate

the analysis presented in Figs. 11 and 12, it can be seen that for the developed FAHP algorithm, the handoff rate is linearly proportional to the transmission time of the SU. This is interesting because the number of handoffs can be estimated using the transmission time, and also, other parameters can be derived from this, such as the delays associated with channel mobility.

5 Conclusions

The developed fuzzy logic analytical hierarchical process (FAHP) algorithm is a tool for decision making that improves efficiency of spectral opportunity selection. This work presents a validation with experimental data captured from the GSM frequency band, although the FAHP application can be extended to other frequency bands.

A methodology by means of a customized Delphi method to carefully select the criteria to be used with the FAHP algorithm is also presented. The Delphi customization comprises not only the experts' decision but also the high-ranked variables reported in the literature on cognitive radio. The parameter selection was carefully chosen for real-time and best-effort applications. According to the results obtained using experimental data of the spectral occupancy, the proposed algorithm provides an efficient selection process for a backup channel with a low computational cost, low delay, high precision, and reduced handoff rate, compared to other decision-making algorithms.

Furthermore, the analysis of the spectrum occupancy performed over the GSM frequency band, specifically at the uplink, shows evidence of high spectral opportunity availability with high-quality spectral characteristics for transmission. These can be ratified with the normalized duty cycle of 25 %, the high availability probability about 90 % for most of evaluated channels, the available estimated time greater than 5 s for half of the channels, and the practical SINR found for most of the channels.

This work also shows that a practical implementation of the proposed FAHP algorithm for cognitive radio is feasible and provides an efficient proactive method for selecting a backup channel. This improves the performance of spectral handoff strategies for proactive cognitive radio devices.

Competing interests

The authors declare that they have no competing interests.

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