Spectral decision for cognitive radio networks in a multi-user environment

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ABSTRACT

Cognitive radio networks promote better spectral efficiency of the electric radio spectrum. The vast majority of current spectral decision models for cognitive radio networks evaluate their performance based on a single secondary user. In reality, the network can experience multiple requests from spectral opportunities. Based on this, the intent of this article is to present and evaluate a spectral decision model for cognitive radio networks in a multi-user environment taking into account the effect of the decisions of the SU on the usefulness of the other SU. To achieve this, a spectral decision model was developed that allows secondary users to share relevant information before accessing the spectrum so that they can select the most appropriate spectral opportunities. The evaluation and validation of the model was performed using three multicriteria decision-making algorithms under the metric of the number of total handoffs in a conventional scenario and a real scenario. In the conventional scenario, only users that match the input of the multiuser module are included; in the real scenario, in addition to the conventional users, users that enter and leave at random times are included, a feature that alters the models for estimating the behavior of the radio environment. The results show better performance of the TOPSIS algorithm over VIKOR and SAW. The most important contribution of this work is the evaluation of the performance of the spectral decision algorithms implemented in a multi-user environment that allows multiple access and exchange of information between users, with experimental spectral occupation data.

1. Introduction

1.1. General context

Next-generation wireless networks will be characterized by faster information transfer and changes in conventional spectrum access policies. Addressing spectrum scarcity challenges and meeting the growing demand for wireless technologies requires access based on approaches that use unlicensed spectrum. This leads to dynamic access, where unlicensed use must ensure fair allocation strategies that improve service quality indicators and also present low levels of interference with other users. Under these characteristics, cognitive radio (CR) will play an increasingly critical role in future wireless communications (Pooja et al., 2021; Srivastava et al., 2021). CR emerged 20 years ago as a technology to overcome scarcity problems using dynamic access to the spectrum. It is characterized by perceiving, learning, planning (decision making) and acting according to current network conditions (Giral et al., 2019; Wang et al., 2020a). In cognitive radio networks (CRNs), unlicensed users (SU) must make smart decisions based on spectrum variation and actions taken by other SU. The accuracy of user decisions is limited and remains a challenge to fully use the benefits of CRNs (Jiang et al., 2014a).

Wireless communication between multiple users is one of the main challenges for deploying next-generation systems. In order to collect global information and expand the user’s limited knowledge of the true state of the system (signals and decisions made by other nodes), users of a CRN must have the ability to recognize changes in the surrounding environment. The information learned will allow to develop a description of the unknown state of the system and improve the accuracy of decisions and, therefore, the efficiency of the network (Wang et al., 2017). When making the decision for channel access, each SU should not only consider channel quality, but must also take into account the channel access decisions of other SU. The more SU who access the same channel, the lower the performance each SU can achieve due to interference between them. This phenomenon is known as negative network externality (Jiang et al., 2014b; Zhang et al., 2012).

1.2. Contributions and scope

This paper describes a module that includes the access of multiple serial users to the CRN decision-making process. Additionally, to include other characteristics associated with the real behavior of the spectral band, the module has the possibility to add random users, without

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2405-8440/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
The proposed scheme has a 45% decrease in the probability of a dropped fair allocation with an accuracy of more than 97% in channel prediction.

The contribution of this work is structured in four input. The first is the development of a multi-user module that implements three multi-criteria techniques: Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi-Criteria Optimization and Compromise Solution (VIKOR). The second input is the evaluation of the performance of the spectral decision algorithms implemented in a multi-user environment that allows multiple access and exchange of information between users. The third input is the consideration of the real behavior of licensed users in the simulation environment from real spectral power measurements. Finally, the fourth contribution is the easy adaptation of the multiuser module to any decision-making strategy. This work implemented three multi-criteria techniques; however, the module is capable of adapting to other multi-criteria techniques, probabilistic strategies, techniques based on artificial intelligence, among others.

1.3. Literature review

Regarding previous multi-user access investigations, there are several applications that can be found. The following are five recent papers on multi-user access in CRN.

(Almasri et al., 2019, 2020) analyze opportunistic access to the spectrum in CR for one or more secondary users (SU) through a priority access policy called All-Powerful Learning (APL). The strategy implemented for multi-user analysis is for users to analyze channel opportunities separately without any cooperation or prior knowledge of available channels. Instead of considering only availability, this proposal takes into account a quality information metric where priority must access only the best channels with the highest availability and quality. The results show that the priority access policy has good results both for a fixed number of users and for dynamic users. An additional highlight is that unlike existing cooperative algorithms, the model does not require prior information or cooperation between users.

(Chakraborty and Misra, 2020) propose a three-phase scheme (proactive phase, reactive phase, and periodic phase) for machine learning-enabled Target Channel Sequence (TCS) allocation and generation. The goal is to design and run a real-time multi-su scheme for Voice over IP (VoIP) communication. The proactive phase performs target channel selection in terms of maximum cumulative channel downtime and minimum number of algorithmic iterations. The reactive phase prevents call drops by providing SU with a pseudorandom sequence of target channels and the periodic phase timely updates the TCS and dynamically maintains the common control channel with the help of the user, channel, and TCS mapping vectors. The results obtained show a reduction in the channel access conflict between multiple SU, ensuring fair allocation with an accuracy of more than 97% in channel prediction. The proposed scheme has a 45% decrease in the probability of a dropped call.

(Wang et al., 2020b) propose a distributed iterative energy efficiency optimization algorithm to obtain Nash equilibrium. Linear precoding techniques are used to mitigate the impacts of multi-user interference and imperfect channel state information. The optimization model is studied under the limitations of perceived interference of Licensed or Primary User (PU) and maximum SU transmission power. To achieve high implementation flexibility and low communication overload, it is considered a non-cooperative game formulation for a fully distributed design, where each pair of SU competes against the other pair of SU optimizing their transmission covariance matrix. The results obtained show that the optimization algorithm reaches Nash equilibrium by converging to the global optimal. The proposed scheme improves energy efficiency, eliminates multi-user interference and alleviates the impact of imperfect channel state information.

(Rizk et al., 2018) review the most relevant cooperative models for decision-making in multi-agent systems (MAS). They present models based on Markov's decision-making processes, game theory, graph theory and swarm intelligence. The different techniques are analyzed according to their optimality criteria and their application. Among the most notable applications are different cognitive systems such as telecommunications networks, electrical systems, transportation systems, search and rescue equipment, object transport, exploration and mapping.

1.4. Organization of the document

This work is organized and presented in four sections. Section 2 describes the methodology. It represents the measurement process carried out of the input variables characterization, the structure, and characteristics of the proposed multi-user module. In the same way, this section also defines the logic of the multi-user search algorithm for the spectral mobility analysis. And finally, it is addressed the decision-making techniques implemented. Section 3 presents the results obtained and the respective quantitative analysis. Section 4 establishes the general conclusions of the work.

2. Materials and methods

In CRNs, the SU must make smart decisions based on spectrum variation and actions taken by other SU. In this dynamic, the probability that two or more SU will choose the same channel is high, especially when the SU number is greater than the number of channels available. Due to the negative externality of the network, the more SU that select the same channel, the lower the utility that each SU can obtain and the number of interferences by simultaneous access will be greater (Abbas et al., 2015). To model the network under practical parameters in reality, it is necessary to analyze the access of multiple users simultaneously.

This work proposes a multi-user module for three multi-criteria decision-making techniques that allow the inclusion of multiple serial users for different types of applications with priority levels and channel bands of different sizes. The following is the methodology description of the developed module.

2.1. Input variables

To carry out the analysis, real power measurements in the GSM frequency band are used as input variables (824–874 MHz). The implemented detection technique was energy detection, due to its simple implementation, low computational cost and low complexity (Ali and Hamouda, 2017; Nallagonda et al., 2021; Youssef et al., 2018). A power threshold of 5 dBm above the noise power was used, in order to determine the spectral occupancy. This decision threshold was based on the average noise floor for the frequency band employed, which is obtained by spectrum analyzer measurements. The protection level was set at -5 dBm above the noise floor, in order to minimize false alarms. Therefore, the average noise floor is -113 dBm, and the decision threshold was set at -113 dBm + 5 dBm = -108 dBm. The equipment for spectral
measurements consists of the Discone Antenna in a frequency range between 25 MHz and 6 GHz, a low noise amplifier in the operating frequency range between 20 MHz and 8 GHz and a spectrum analyzer in the operating frequency range between 9 kHz and 7.1 (Hernández Suárez et al., 2016). Figure 1 presents the experimental structure used for the measurement of spectral occupancy.

The characteristics and configuration of the technical parameters of the measurement carried out are described in Table 1. The spectrum analyzer measures the power level in dBm for 500 frequency channels with a bandwidth of 100 kHz each.

According to the sweep time value (Table 1) and the measurement period, which was one month, it generated a database with 4,468,608,000 measurements; the previous measurement information allowed to characterize a power matrix of 8,937,216 rows and 500 columns. Table 2 presents the data of the power matrix obtained according to the measurements made. The rows represent the time in seconds (each instant of time equals 290 ms), and the columns represent the channels or frequencies. From the information of the 500 frequency channels, two matrices were constructed. The first is used as a training matrix and contains the information of one hour of the spectral occupation. The second is used as an evaluation matrix and contains the information of nine minutes of the spectral occupation.

2.2. Structure of the implemented module

Figure 2 presents the block diagram of the multi-user module. The blocks where the input and output signals converge correspond to the programming functions used for user characterization. The general idea of the module is to analyze the behavior of spectral decision models when multi-user access is presented. To achieve this goal, multiple users are generated with different requirements. The module can handle four types of bands (applications). Each of these bands has the possibility to request priority and access to multiple channels. The multiple users and their respective characteristics will be part of the model throughout the simulation time. This methodology was named "Conventional Mode". The module has the possibility to include random users, without interest of analysis, who appear at random times without being present the entire simulation time but who have characteristics similar to the users who participate in the whole process. This structure was named "Real Mode". To generate metrics, the multiple users are introduced into a search algorithm that will analyze the behavior of spectral handoffs. The description of each of the input variables and their respective adjustment are presented in Table 3. The methodologies implemented for each of the blocks in Figure 2 are described in detail in the following subsections. Subsections 2.3, 2.4 and 2.5 describe the "User Characteristics", "Number of Users" and "Channel Priority" blocks, respectively. Subsection 2.6 describes the logic developed for the "Multi-user search Algorithm". Finally, subsection 2.6 describes the decision-making models implemented in the "Decision-Making Models" block.

2.3. User characteristics

The user characteristics establish the number of multichannel bands, the number of channels per band, the priority, and the percentage of users who will have these characteristics. The goal is to handle different channel demand scenarios per user. The multichannel bands represent the type of application, and the number of channels, the bandwidth demand and/or the requirement according to the type of application which can be single channel or multi-channel. Priority assignment is performed according to the order in which the information is adjusted. Figure 3 shows the settings for user characteristics.

A particular description for user characteristics is presented in Figure 4. For the specific case, three multichannel bands (three types of applications) are selected, the highest priority band requires three bandwidth channels, the bandwidth band with the second priority requires two bandwidth channels, and the third priority bandwidth band requires four bandwidth channels. According to the information in Figure 4, 25 % of users will take priority 1, 50 % of users will take priority 2 and 25 % of users will take priority 3.

2.4. Number of users

The number of users depends on the simulation mode: Conventional Mode and Real Mode as shown in Figure 5. To establish the total number of users, a demultiplexing block is required. If the conventional mode is used, the user assignment and random time is disabled and therefore the total number of users corresponds to the "Number Serial Users". If real mode is used, the user block and random time is enabled and therefore the total number of users increases with regards to conventional mode. The following is the description of the methodology used for parameterization of the number of users.

2.4.1. Total users

Total users are quantified based on the adjusted mode: Conventional Mode and Real Mode. Algorithm 1 introduces the implemented programming structure. It is not possible for both modes to be enabled simultaneously. The "Random Time" output will only be available for real mode.

Algorithm 1. Structure for total users assignment
Input: Number Serial Users, Simulation Mode
Output: Total Users, Random Time
Select the simulation mode (Real Mode or Disabled Mode)
Select number of serial users (NSU)
Define the simulation time (ST)

Table 1. Parameters for the measurement of spectral occupancy.

| Parameter                        | Value                     |
|----------------------------------|---------------------------|
| Characteristics of measurement   | Sweep time                |
|                                  | Resolution of bandwidth   |
|                                  | Span                      |
| Sweep time                       | 290 ms                    |
| Bandwidth resolution             | 100 kHz                   |
| Span                             | 50 MHz                    |
| Band Frequency                   | 824–874 MHz               |
| Cannals number                   | 500                       |
| Detection Technique              | Energy detection          |

Table 2. Captured data.

| Frequency band | Quantity of Data Captured |
|----------------|---------------------------|
| GSM            |                           |
|                | Rows                      |
|                | Columns                   |
|                | Total Data                |
|                | 8,937,216                 |
|                | 500                       |
|                | 4,468,608,000             |

MP Antenna
Super-M Ultra Rare
25 MHz - 6 GHz
8 dBm

Low Noise Amplifier
Gain: 8 - 11.5 dB
Noise Figure: 4 - 4.5 dB
20 - 8000 MHz

Power Measurements
Spectrum Analyzer
9 MHz - 7.1 GHz

Figure 1. Block diagram for the measurement of spectral occupancy.
2.4.1.1. Conventional mode. Conventional mode does not generate random users or random time. The total number of users, as described in Algorithm 1 corresponds to the user parameter that conforms to the model input.

2.4.1.2. Real mode. The objective of this mode is to analyze real system characteristics. During a transmission time, there are various events associated with user behavior. Users are constantly entering and exiting at indefinite times, altering the behavior estimation models of the radio environment. The real mode allows the inclusion of users in the simulation different from the users of interest, who will not be present the entire simulation time and that enter and exit at random times. For the

Table 3. Description of the input variables for the multi-user module.

| Variable          | Adjustment | Description                                                                 |
|-------------------|------------|-----------------------------------------------------------------------------|
| Multichannel Bands| 1-4        | Number of applications selected for simulation                             |
| Channels          | 1–10       | Number of channels required for each selected application                   |
| Percentage        | 25%–50% − 75%–100% | Percentage of users who acquire the characteristic of the app and of the number of channels |
| Number Serial Users| 1–30    | Number of SU that simultaneously access the spectrum. These users are characterized by exchanging information among themselves prior to initiating the opportunistic access process |
| Simulation Mode   | Real Mode  | Random users are included                                                   |
|                   | Conventional Mode | Random users are not included                                             |
| Simulation Time   | 1–9 min    | Average time that an SU occupies the frequencies assigned to the PU        |
| Availability Matrix| GSM      | Matrix containing spectral availability information                      |

If Real Mode Enabled and Conventional Mode Disabled
Random Time Enabled
Random Users Enabled
Set the number of random users
Random Users = randperm(1, max(NSU))
Set the entry time for each of the random users
Set the exit time for each of the random users
Random Time = randperm(0.3*ST, 0.7*ST)
Set total users
Total Users = Number of Serial Users + Random Users
end

% Total Users Real Mode
If Real Mode Enabled and Conventional Mode Disabled
Random Time Enabled
Random Users Enabled
Set the number of random users
Random Users = randperm(1, max(NSU))
Set the entry time for each of the random users
Set the exit time for each of the random users
Random Time = randperm(0.3*ST, 0.7*ST)
Set total users
Total Users = Number of Serial Users + Random Users
end

% Total Users Conventional Mode
number of random users, an integer evenly distributed between one and the maximum user value that conforms to the model input is generated, which means that the number of random users can never exceed conventional users. If random users remained throughout the whole simulation time, the real model would have the same behavior as the conventional model, so random users enter and exit at times other than those established in the conventional model. By design criteria, a random user will only be able to enter when 30% of the SU transmission in minutes is exceeded, and will be able to participate in the spectral decision process up to 70% of the SU transmission in minutes. To establish the stay time with the criteria previously described, an ascending random integer vector of two positions is generated with a range of 30–70, equivalent to the time percentages for input and output. Figure 6 shows the user and random time assignment diagram, which corresponds to one (1) and the time limits for the login (30%) and logout (70%) of the random users. The probability distribution employed corresponds to a uniform distribution (Matlab randperm function).

2.5. Channel priority

As described in section 2.3, priority assignment is performed according to the order of adjustment of the information. The priority includes the information associated with the application (band) and the number of channels. If conventional mode is used, the total number of users for each priority is based on proportionality, allocated in each percentage relationship of the user’s characteristics. Algorithm 2 introduces the structure for channel priority in conventional mode.

Algorithm 2. Conventional mode channel priority

**Input:** Number Serial Users, Simulation Mode

**Output:** Total Users, Random Time

Conventional simulation mode selected

Define the number of multichannel bands
Define the percentage of users per priority (PP)

% Total Users Real Mode

If Real Mode Disabled and Conventional Mode Enabled

Random Time Disabled

Random Users Disabled

Set Total Users

Total Users = Number of Serial Users

Set the priority according to the number of multichannel bands

If the number of multichannel bands is equal to one

Users_Priority_1 = PP_1 * Total Users

elseif Number of multichannel bands is equal to two

Define percentage of users for each priority (PP_1 and PP_2)

Users_Priority_1 = PP_1 * Total Users

Users_Priority_2 = PP_2 * Total Users

elseif Number of multichannel bands is equal to three

Define the percentage of users for each priority (PP_1, PP_2, and PP_3)

Users_Priority_1 = PP_1 * Total Users

Users_Priority_2 = PP_2 * Total Users

Users_Priority_3 = PP_3 * Total Users

elseif Number of multichannel bands is equal to four

Define the percentage of users for each priority (PP_1, PP_2, PP_3, and PP_4)

Users_Priority_1 = PP_1 * Total Users

Users_Priority_2 = PP_2 * Total Users

Users_Priority_3 = PP_3 * Total Users

Users_Priority_4 = PP_4 * Total Users

end

end

For real mode channel priority, random users are first required to be located, and from this criterion priority assignment is performed.

2.5.1. Random user location

It is important to differentiate the stay time of a random user and the location of a random user in the multi-user structure. For the stay time, a random user will only be able to log in when 30% of the SU transmission in minutes is exceeded and up to 70% of the SU transmission in minutes. The location is only analyzed at the time the random user enters, as shown in Figure 7. A random user can be located at the beginning, end and intermediate position of conventional users. The location is done through a random structure, as shown in Figure 7. The priority of conventional users is not affected.

2.5.2. Priority assignment

Each random user must obtain a priority which is assigned based on the location and percentage of users in each priority. To understand this assignment, Figure 8 presents an example with three conventional users and a random user. The random user was located among users with priority 1 and priority 2. As previously described, the location was randomly selected. For the assigned characteristics, 25% of users will have priority 1, 50% will have priority 2 and 25% will have priority 3. Therefore, only one user will have priority 1 (the criterion of the largest integer is handled since it is not possible to define decimal users), two users will have priority 2 and one user will have priority 3. The selection of users is done in order of location. Therefore, and as described in Figure 8, the random user acquires the characteristics of users with priority 2.

2.6. Multi-user search algorithm

This algorithm is in charge of the spectral mobility analysis. It requires an input vector called Ranking which has the information of the positions of the channels. These positions are obtained by the scores determined by the multicriteria decision-making models. The channels with the highest scores are placed in the first positions of the Ranking vector and the channels with the lowest scores are located in the last positions of the Ranking vector.

According to the Ranking position vector, the search algorithm performs column breaks in the availability matrix until an available channel is found. Upon finding a channel, it makes a row change (time instance) in the availability matrix. Column breaks, row breaks, time, and availability are stored in a vector and given feedback at the end of the simulation in a database. Algorithm 3 shows the structure for the spectral mobility analysis of a user.

The process is equivalent for a user with a channel, which for multiple users with multiple channels, the most relevant difference is presented in the row change (time instance), which for multiple users, is only made when all users find spectral opportunities or when channel requirements are higher than the availability.

For a multi-user search, the algorithm can find itself in two scenarios. The first scenario is where all users find spectral opportunities for all the
channel requirements and the second scenario is where spectral opportunities are less than the requirements of multiple users. For the latter case, the algorithm reports the event and then jumps to start the search again in the next time instance.

**Algorithm 3.** Search algorithm for a user

**Input:** Simulation Time, Available, Ranking  
**Output:** Handoff

1. Set an initial position per row ($i = \text{time}$) and per column ($j = \text{channel}$)
   
   $i = 1; j = 1$

2. Initiate global Handoff variable (Handoff)
   
   Handoff = 0

3. While $i < \text{Simulation Time}$ do
   
   a. Start the Elapsed Time Counter
      
      time = time + 1
   
   b. Store the current channel availability status
      
      Availability = Available ($i, \text{Ranking}(j)$);
   
   c. Evaluate whether the channel is busy or available
      
      switch Availability
      
      - Busy channel
        
        a. The channel change is made, the next position is assigned by the MCDM ranking
          
          $j = j + 1$;
        
        b. The Handoff counter increases
          
          Handoff = Handoff + 1;
      
      - Available channel
        
        a. Row change is performed
          
          $i = i + 1$;
        
        b. The handoff counter is not increased

4. End

**2.6.1. Multi-user spectral mobility scenarios**

Figure 9 presents two spectral mobility scenarios for multiple users in conventional mode, or in real mode if the transmission minutes of the SU is less than 30 % or greater than 70 %. There are three users. For this particular case, priority 2 has a percentage of 50 % while priorities 1 and 3 have 25 %, obviously in whole numbers. The user assignment for each priority is not possible. The module is reconfigured and assigns to each priority a percentage of 33 %. Therefore, each priority will have a single user. The goal of the search algorithm is to find the spectral opportunities.
(available channels) according to the Ranking vector, where the lowest value in the position of the Ranking vector corresponds to the channels with the highest probability of availability.

For the first scenario of Figure 9, the user with priority 1 and with a requirement of 3 channels, finds spectral opportunities in Ranking vector positions (1 2 3). The user with priority 2 and with a requirement of 2 channels, finds spectral opportunities in Ranking vector positions (5 6). It is not possible to occupy position (4) since the channel is occupied by a PU. Additionally, the algorithm does not perform the search on channels (1 2 3). Prior to the assignment made to users with priority 1, the module receives feedback and reports that these channels are not available. Finally, the user with priority 3 and with a requirement of 4 channels, finds spectral opportunities in Ranking vector positions (7 9 10 11). It is not possible to occupy position (4) since the channel is occupied by a PU. As all users find spectral opportunities for all channel requirements, the algorithm performs a row break and starts the search again.

For the second scenario in Figure 9, the channel requirements are higher than the availability. At the end of the search, users with priority 3 and with 4 channel requirements find only two spectral opportunities of the 4 they require. For this particular case, the module reports on the result, does a row break and starts the search again. Column breaks, row breaks, time, and availability per user are stored in a vector and given feedback at the end of the simulation in a database.

Figure 10 presents a spectral mobility scenario for multiple users in real mode. There are three conventional users and one random who acquire the characteristics of priority 2 (example described in the assignment of prioritization in Section 2.5). For this particular case, priority 2 has a percentage of 50% while priorities 1 and 3 have 25%. Therefore, priority 2 will have two users and priority 1 and 3 a single user.

According to the scenario described in Figure 10, the user with priority 1 and with a requirement of 3 channels, finds spectral opportunities in Ranking vector positions (1 2 3). For priority 2, there are two users with a requirement of two channels per user. The random one finds spectral opportunities in Ranking vector positions (4 6), and the conventional one in Ranking vector positions (7 8). It is not possible to occupy position (5) since the channel is occupied by a PU. Finally, the user with priority 3 and with a requirement of four channels, finds spectral opportunities for only three of the four channels in Ranking vector positions (9 10 11). The module reports on the result, performs a row break and starts the search again.

2.7. Decision-making models

The decision-making process in CRN has multiple challenges and variables to analyze. As well as these challenges, the strategies available are diverse. There is a large number of studies that analyze or compile strategies for the decision-making process. However, there is no single best technique; each structure has a considerable number of advantages and disadvantages, which makes it possible to characterize them for specific decision-making problems. A classification of decision-making algorithms in CRN is described in (Giral et al., 2019; Rizk et al., 2018; Wang et al., 2020a).

Based on the literature review, multi-criteria decision-making techniques (MCDM) were selected for the decision-making process of the proposed module. This selection was done taking into account that MCDM methods are a suitable mathematical tool for decision-making (Gheorghe et al., 2018; Jayakumar and Janakiraman, 2019). MCDM are characterized by involving multiple decision variables, which are prioritized through the assignment of weights, essential elements for the analysis of multi-user access in CRN. Additionally, in the area of decision-making in CRN, MCDM are used for their efficient results (Aguilar-Gonzalez and Ramos, 2018; Rodriguez-Colina et al., 2020) and for their low computational burden.

Figure 11 describes the decision-making process using MCDM. The block in charge of multi-criteria analysis is called the "MCDM Algorithm"; it requires decision vectors (decision criteria) and weight vectors (W) as input parameters. The decision vectors correspond to: Average of each column of the availability matrix (AP), Average of some consecutive of the availability matrix (AAT), Average of each column of the SINR matrix without including zeros (PSINR) and Average of each column of the bandwidth matrix (ABW). The weight vectors correspond to the weights assigned to each decision criterion, with one (1) as the best score and zero (0) as the lowest score.

According to the decision vectors and the weight vectors, a score vector is generated, which organizes the channels in a descending manner. In the first positions are the canals with the best scores. On the contrary, canals with the lowest scores are in the last place. Eq. (1) allows the calculation of the allocation of scores, where \( W_{AP} \), \( W_{AAT} \), \( W_{PSINR} \), \( W_{ABW} \) correspond to the weights of each decision criterion.

\[
Score = \omega_{AP}(AP) + \omega_{AAT}(AAT) + \omega_{PSINR}(PSINR) + \omega_{ABW}(ABW)
\]

Eq. (1) allows assigning a score to each channel. However, it is necessary to carry out an additional study for decision making; this study establishes a classification of the canals for the SU data transmission process through the score vector and the MCDM. The result is the output block of the " MCDM Algorithm " and corresponds to a vector called ranking. As described in the search algorithm, this vector sets the positions for the column breaks in the availability matrix. Aim to generate a comparative analysis; this work uses three MCDM: SAW, TOPSIS and VIKOR. These techniques have presented excellent results in decision-making.
making investigations with MCDM for CRN that is why they were selected (Divya & Nandakumar, 2019; Jayakumar and Janakiraman, 2019; Jayakumar et al., 2019; Prasad and Jaya, 2019; Rodríguez-Colina et al., 2020). Table 4 presents the mathematical model for SAW, VIKOR, and TOPSIS.

The weights of each of the multicriteria techniques were determined with the Delphi method (Hernandez et al., 2015) and are described in Table 5.

2.8. Performance metric

The evaluation of the implemented strategy is carried out through spectral mobility metrics. Spectrum mobility is defined as the process in which a SU changes its frequency of operation, when the conditions of a channel degrade, or when a licensed user appears. The process by which the SU switches from one frequency channel to another is known as spectral handoff (Akyildiz et al., 2006, 2008; Lam et al., 2013).

The concept of spectral handoff in CR differs from the traditional mechanisms of wireless networks by the characterization and priority that is assigned to users. Each time a spectral handoff occurs, the CRN operating parameters change to minimize the impact on the operation of the SU. Spectral handoff analysis is performed through the availability matrix, simulation time, number of users, and respective application characteristics. The total number of handoffs performed during the SU transmission is used as a metric.

3. Results

The results achieved are presented through the metrics associated with the performance of the algorithm and the comparative analysis of the decision-making strategies analyzed. The implementation was done on a computer with a 2.8 GHz Intel (R) Core (TM) i7-7700HQ processor with 24 GB of RAM, Microsoft Windows 10 64-bit operating system using MATLAB version R2020a.

The results are structured using three comparative analyses. The first establishes the handoff metric for ten different multi-user structures: 1 SU, 2 SU, 3 SU, 4 SU, 5 SU, 6 SU, 7 SU, 8 SU, 9 SU and 10 SU during nine minutes of transmission. This is shown in Figures 12, 13, 14, 15, 16, and 17 for the SAW, TOPSIS and VIKOR techniques, in conventional mode and real mode. The second analysis describes the ten multi-user scenarios for minute nine in conventional mode and in real mode for the total number of handoffs. This is shown in Figures 18, 19, and 20 for the SAW, TOPSIS and VIKOR techniques, respectively. Finally, the third analysis compares the multi-criteria strategies for the ten different multi-user structures in conventional mode and the real mode as shown in Figures 21 and 22.

3.1. Number of handoffs for ten different multi-user structures

Figures 12 and 13 presents the metric for the SAW decision-making in conventional mode and real mode. During the nine minutes of transmission...
transmission, the best performance with the least number of handoffs is for the scenario with 1 SU and the lowest performance with the highest number of handoffs is for the scenario with 10 SU. For intermediate scenarios, during the first three minutes there were variations in the order of performance. After the third minute, the scenarios with the highest number of handoffs were for the range of 6 SU to 9 SU. In the real mode, the same behavior is presented with an increase in the total handoffs.

Figures 14 and 15 presents the metric for the TOPSIS decision-making in conventional mode and real mode. During the nine minutes of transmission, the lowest performance with the highest number of handoffs was for the scenario with 10 SU. The best performance with the fewest handoffs was for the scenario with 1 SU. With the exception of minute two, where it ranked in third place of performance being surpassed by the scenario of 2 SU and 3 SU. For intermediate scenarios, from the first minute, the largest number of handoffs was for the range of 6 SU to 9 SU. For intermediate scenarios, from the first minute, the largest number of handoffs was for the range of 2 SU to 5 SU. In the real mode, the same behavior was presented with an increase in the total handoffs.

Figures 16 and 17 presents the metric for the VIKOR decision-making in conventional mode and real mode. During the nine minutes of transmission, the best performance with the least number of handoffs was for the scenario with 1 SU and the lowest performance with the highest number of handoffs was for the scenario with 10 SU. For intermediate scenarios, during the first minute, the largest number of handoffs was for the range of 6 SU to 9 SU. With the exception of minute two, where it ranked in third place of performance being surpassed by the scenario of 2 SU and 3 SU. For intermediate scenarios, from the first minute, the largest number of handoffs was for the range of 2 SU to 5 SU. In the real mode, the same behavior was presented with an increase in the total handoffs.

### 3.2. Total handoffs in conventional mode and in real mode

Figure 18 presents the comparative analysis for SAW. The best performance with the fewest total handoffs is for the conventional mode with the exception of the scenarios of 5 SU and 9 SU, where the real mode exceeded the conventional mode by 44 and 16 total handoffs, respectively. The biggest difference was in the 2 SU scenario with 284 total handoffs and the smallest difference was in the 9 SU scenario with 16 total handoffs.

Figure 19 presents the comparative analysis for TOPSIS. The best performance with the fewest total handoffs was for conventional mode with the exception of the scenario of 10 SU where the conventional mode exceeded the real mode by 77 handoffs. The biggest difference was in the 4 SU scenario with 363 handoffs and the smallest difference was in the 2 SU scenario with 27 total handoffs.

Figure 20 presents the comparative analysis for VIKOR. The best performance with the fewest total handoffs was for the conventional mode. The biggest difference was in the 3 SU scenario with 359 handoffs and the smallest difference was in the 1 SU scenario where the total number of handoffs was equal in the conventional mode and real mode.

### 3.3. Total handoffs and multi-criteria techniques in conventional mode and in real mode

Figure 21 presents the comparative analysis in the conventional mode for the three decision-making strategies. VIKOR has the lowest performance for the range of 1 SU to 10 SU. For the range of 1 SU to 3 SU, VIKOR presents an improvement in results. However, it continues with the lowest performance with respect to SAW and TOPSIS. For scenarios of 1 SU to 5 SU and 9 SU to 10 SU, TOPSIS provides the best metrics with the lowest total handoff levels. For the range of 6 SU to 7 SU, SAW provides the best metrics with the lowest total handoff levels.

Figure 22 presents the real mode comparative analysis for the three decision-making strategies. VIKOR presents the lowest performance for the range of 1 SU to 10 SU. For all other scenarios, TOPSIS provides the best metrics with the lowest total handoff levels. For scenarios of 1 SU to 4 SU and 9 SU to 10 SU, TOPSIS provides the best metrics with the lowest total handoff levels. For the range of 5 SU to 7 SU, SAW provides the best metrics with the lowest total handoff levels.

### 3.4. Discussion

For the three different decision-making models—in conventional mode and in real mode—there is an increase in the performance of the multicriteria technique in terms of the number of users. The best performance with the fewest number of handoffs accumulated is for the scenario with 1 SU and the lowest performance with the highest number of handoffs accumulated is for the scenario with 10 SU.

For the SAW decision-making model in conventional mode, it was identified that the number of handoffs had a stable increase according to the transmission time. This indicates that for each time instance, the number of handoffs grow in the same ratio, which is measured with respect to the scenario with the least number of handoffs. Additionally, the ratio increases as the number of users increases. The average increase in the number of handoffs for scenarios of 2 SU, 3 SU, 4 SU, 5 SU, 6 SU, 7 SU, 8 SU, 9 SU, 10 SU is 35 %, 54 %, 55 %, 60 %, 54 %, 60 %, 71 %, 88 %, 98 %, respectively. For the real mode, the increase in the number of handoffs has the same behavior. It is stable according to the transmission time.
time and increases as the number of users increases. There is a slight increase in the average percentages of the scenarios. For 2 SU, 3 SU, 4 SU, 5 SU, 6 SU, 7 SU, 8 SU, 9 SU y 10 SU, the increase is 42 %, 53 %, 57 %, 54 %, 56 %, 61 %, 74 %, 88 %, 103 % respectively.

The TOPSIS decision-making model in conventional mode identified the formation of two sets of scenarios with stable growths relative to the scenario with the fewest number of handoffs. The first set corresponds to the range of scenarios from 2 SU to 4 SU where the average increase is 32 %. The second set corresponds to the range of scenarios from 5 SU to 10 SU where the average increase is 97 %. In addition, it is noted that above-average variations occurred for transmission times less than three minutes. For the real mode, the increase in the number of handoffs has the same behavior, with a slight increase in the average percentages of the two sets of scenarios, for the scenario range of 2 SU to 4 SU, the average increase was 39 % and for the set of scenarios from 5 SU to 10 SU it was 98 %.

For the VIKOR decision-making model in conventional mode, the formation of three sets of scenarios with stable growths relative to the scenario with the fewest number of handoffs were identified. The first set corresponds to the range of scenarios from 8 SU to 10 SU where the average increase doubled the handoffs with a ratio of 106 %. The second set corresponds to the scenario range of 5 SU to 7 SU where the average increase was 84 %. Finally, the third set corresponds to the scenario range of 2 SU to 4 SU where the average increase was 40 %. In addition, it
is noted that above-average variations occurred for transmission times less than four minutes. For the real mode, the increase in the number of handoffs has the same behavior, with a slight increase in the average percentages of the three sets of scenarios, for the scenario range of 8 SU to 10 SU, the average increase was 107 %, for the set of scenarios from 5 SU to 7 SU it was 85 %, and for the set of scenarios of 2 SU to 4 SU it was 50 %.

From the comparison analysis of total handoffs in conventional mode and in real mode, it is identified that the biggest difference was obtained in the scenario of 4 SU for TOPSIS with 363 total handoffs, followed by VIKOR in the scenario of 3 SU with 359 total handoffs, and SAW was third with 284 total handoffs in the 2 SU scenario. The smallest difference was obtained in VIKOR for the 1 SU scenario where the total number of handoffs was equal for the conventional mode and real mode, SAW came in second for the 9 SU scenario with 16 total handoffs, and finally TOPSIS in the 2 SU stage had 27 total handoffs. In general, the real mode performance is lower than the conventional mode for SAW, TOPSIS, and VIKOR. This feature is present because the addition of random users reduces spectral opportunities and is therefore, they are more difficult to locate, resulting in an increase in the number of handoffs.

In the conventional mode, for the three decision-making strategies and according to the comparative analysis between the number of total handoffs and multi-criteria models, VIKOR has the lowest performance for the range of 4 SU to 10 SU. The average difference with regards to the
best performing model is 454 total handoffs. The biggest difference is in
the 8 SU scenario with 567 total handoffs and the smallest difference is in
the 5 SU scenario with 270 total handoffs. For the range of 1 SU to 3 SU,
VIKOR shows an improvement in results. However, it continues having
the lowest performance with respect to SAW and TOPSIS. The average
difference with respect to the model with the best performance was 180
total handoffs, the biggest difference was in the scenario of 3 SU with 246
total handoffs and the smallest difference was in the scenario of 1 SU with
137 total handoffs. Regarding SAW and TOPSIS, in the range of 6 SU to 8
SU, SAW obtained the best performance with the lowest total handoff
levels. For all other scenarios, TOPSIS provides the best metrics with the
lowest total handoff levels.
In the real mode for the three decision-making strategies and ac-
cording to the comparative analysis between the number of total hand-
offs and multi-criteria models, VIKOR has the lowest performance for the
range of 2 SU to 10 SU. The average difference with respect to the model
with the best performance was 472 total handoffs, the biggest difference
was in the 7 SU scenario with 543 total handoffs and the smallest dif-
ference was in the 4 SU scenario with 388 total handoffs. For the 1 SU
scenario, VIKOR showed an improvement in results. However, it con-
tinues with the lowest performance compared to SAW and TOPSIS. The
difference was respect to the best performing model was 20 total hand-
offs. Regarding SAW and TOPSIS, in the range of 5 SU to 8 SU, SAW
obtained the best performance with the lowest total handoff levels. For
The total number of handoffs is used as the performance metric. The results are presented from three comparative analyses for ten different multi-user structures: 1 SU, 2 SU, 3 SU, 4 SU, 5 SU, 6 SU, 7 SU, 8 SU, 9 SU, and 10 SU, in conventional mode and in real mode. According to the cumulative cost metric analyzed, the best performance with the fewest total handoffs is for the scenario with 1 SU. The lowest performance is for the scenario with 10 SU. The behavior described is seen in the conventional mode and the real mode. For analysis based on the transmission time and decision-making model, relationships are evident between the number of users and the increase in handoffs. For SAW, the number of handoffs increases as the number of users increases. For TOPSIS, the number of handoffs increases according to two ranges of scenarios. The largest increase is for the range of scenarios from 5 SU to 10 SU and the smallest increase is for the range of scenarios from 2 SU to 4 SU. For VIKOR, the number of handoffs increases according to three scenario ranges. The largest increase is for the range of scenarios from 5 SU to 10 SU and the smallest increase is for the range of scenarios from 2 SU to 4 SU. For VIKOR, the number of handoffs increases according to three scenario ranges. The largest increase is for the range of scenarios from 5 SU to 10 SU, an intermediate increase is for the scenario range from 5 SU to 7 SU and the lowest increase is for the scenario range from 2 SU to 4 SU. Real mode performance is lower than conventional mode. Incorporating random users reduces spectral opportunities and are therefore more difficult to locate. With regard to the multicriteria models implemented for decision making, it is clear that as the number of users increases, the performance of SAW, TOPSIS and VIKOR decreases. In general, TOPSIS provides the best metrics with the lowest total handoff levels.

4. Conclusion

A multi-user module was developed to analyze the effect of SU decisions on the usefulness of the other SU. The module has two simulation modes: conventional mode and real mode. In the real mode, users are included who are different from the users of interest and who will not be present the entire simulation time since they enter and exit at random times. In the conventional mode, only the behavior of the users of interest is included. For the access of multiple users, the SU share information before accessing the spectrum to make the respective decisions and do not contemplate the exchange of information after the decision-making process. The decision-making process is done through three multi-criteria models: SAW, TOPSIS and VIKOR.

Figure 22. Real analysis of the conventional mode for SAW, TOPSIS and VIKOR.

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References

Abbas, N., Nasser, Y., Ahmad, K. EL, 2015. Recent advances on artificial intelligence and learning techniques in cognitive radio networks. EURASIP J. Wirel. Commun. Netw. 174, 1–20.
Aguilar-Gonzalez, R., Cardenas-Juarez, M., Pineda-Rico, U., Stevens-Navarro, E., 2014. Performance of MADM algorithms with real spectrum measurements for spectrum decision in cognitive radio networks. In: 2014 11th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), pp. 1–6.
Aguilar-Gonzalez, Rafael, Ramos, V., 2018. In: Arya, K.V., Bhadoria, R.S., Chaudhari, N.S. (Eds.), Spectrum Decision Mechanisms in Cognitive Radio Networks BT - Emerging Wireless Communication and Network Technologies: Principle, Paradigm and Performance. Springer Singapore, pp. 271–296.
Akyildiz, I.F., Lee, W.-Y., Vuran, M.C., Mohanty, S., 2008. A survey on spectrum management in cognitive radio networks. Communications Mag. IEEE 46 (4), 40–48.
Akyildiz, Ian F., Lee, W.-Y., Vuran, M.C., Mohanty, S., 2006. NeXt generation/dynamic spectrum access/cognitive radio wireless networks: a survey. Comput. Network. 50 (13), 2127–2159.
Ali, A., Hamouda, W., 2017. Advances on spectrum sensing for cognitive radio networks: theory and applications. IEEE Communications Surveys Tutorials 19 (2), 1277–1304.
Almazri, M., Mansour, A., Moy, C., Assoum, A., Osswald, C., Jeune, D.L., 2019. All powerful learning algorithm for the priority access in cognitive network. In: 2019 27th European Signal Processing Conference (EUSIPCO), pp. 1–5.
Almazri, Mahmoud, Mansour, A., Moy, C., Assoum, A., Lejeune, D., Osswald, C., 2020. Dynamic decision-making process in the opportunistic spectrum access. Adv. Sci. Technol. Eng. Syst. J. 5 (4), 223–233.

Declarations

Author contribution statement

Diego Giral, Cesar Hernández & Camila Salgado: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
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Chalraborsty, T., Misra, I.S., 2020. A novel three-phase target channel allocation scheme for multi-user Cognitive Radio Networks. Comput. Commun. 154, 18–39.

Divya, A., Nandakumar, S., 2019. Adaptive threshold based spectrum sensing and spectrum handoff using MADM methods for voice and video services. In: 2019 International Conference on Vision towards Emerging Trends in Communication and Networking (VITECOIN), pp. 1-6.

Gheorghe, A.V., Vamanu, D.V., Katinas, P.F., Pulfer, R., 2018. In: Gheorghe, A.V., Vamanu, D.V., Katinas, P.F., Pulfer, R. (Eds.), Managerial Vulnerability Assessment Models BT - Critical Infrastructures, Key Resources, Key Assets: Risk, Vulnerability, Resilience, Fragility, and Perception Governance. Springer International Publishing, pp. 175–196.

Giral, D., Hernández, C., Martínez, F., 2019. Algoritmos para Toma de Decisiones en Redes Inalámbricas Cognitivas: una Revisión. Inf. Technol. 50 (6), 387–402.

Hernández, C., Salgado, C., López, H., Rodríguez-Colina, E., 2015. Multivariable algorithm for dynamic channel selection in cognitive radio networks. EURASIP J. Wirel. Commun. Netw. 2015 (1), 216.

Hernández Suárez, C.A., Pedraza Martínez, L.F., Rodríguez de la Colina, E., 2016. Fuzzy feedback algorithm for the spectral handoff in cognitive radio networks. Redin 80, 47–62.

Jayakumar, L., Janakiraman, S., 2019. A novel need based free channel selection scheme for cooperative CRN using EFAHP-TOPSIS. J. King Saud Univ. Comput. Inf. Sci. 3190.

Jiang, C., Chen, Y., Liu, K.J.R., 2014a. Multi-channel sensing and access game: Bayesian social learning with negative network externality. IEEE Trans. Wireless Commun. 13 (4), 2176–2188.

Jiang, C., Chen, Y., Liu, K.J.R., 2014b. Sequential multi-channel access game in distributed cognitive radio networks. In: 2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP), pp. 1247–1251.

Kumar, K., Prakash, A., Tripathi, R., 2017. Spectrum handoff scheme with multiple attributes decision making for optimal network selection in cognitive radio networks. Digit. Communications Netw. 3 (3), 164–175.

Lam, A.Y.S., Li, V.O.K., Yu, J.J.Q., 2013. Power-controlled cognitive radio spectrum allocation with chemical reaction optimization. IEEE Trans. Wireless Commun. 12 (7), 3180–3190.

Loganathan, J., Latchoumi, T.P., Janakiraman, S., Parthiban, L., 2016. A novel multi-criteria channel decision in co-operative cognitive radio network using E-TOPSIS BT. In: International Conference on Informatics and Analytics, ICGA, 25-26-Aug, TEQIP II NPRI.

Nallagontha, S., Mammidi, R., Bhownick, A., 2021. Analysis of energy-efficient cooperative spectrum sensing with improved energy detectors and multiple antennas over Nakagami-q/n fading channels. Int. J. Commun. Syst. 34 (5), e4731.

Pooja, A.S., Theresa, R., Govind, S., Mary, A.A., 2021. In: Suresh, P., Saravanakumar, U., Hussein Al Salameh, M.S. (Eds.), Detection of Byzantine Attack in Cognitive Radio Network BT - Advances in Smart System Technologies. Springer Singapore, pp. 459–468.

Prasad, R.K., Jaya, T., 2019. Optimal network selection in cognitive radio network using simple additive weighting method with multiple parameters. In: 2019 International Conference on Smart Systems and Inventive Technology (CSSIT), pp. 715–721.

Ramírez-Perez, C., Ramos-R, V., 2013. On the effectiveness of multi-criteria decision mechanisms for vertical handoff. In: International Conference on Advanced Information Networking and Applications, pp. 1157–1164.

Riaz, Y., Awad, M., Tunestol, E.W., 2018. Decision making in multiagent systems: a survey. IEEE Trans. Cognit. Dev. Syst. 10 (3), 514–529.

Rodriguez-Colina, E., Giral, D., Hernández, C., 2020. Spectrum decision-making in collaborative cognitive radio networks. Appl. Sci. 10 (19), 6786.

Rodriguez-Colina, E., Ramírez, P., Carrillo, A., Ernesto, C., 2011. Multiple attribute dynamic spectrum decision making for cognitive radio networks. In: International Conference on Wireless and Optical Communications Networks, pp. 1–5.

Srivastava, A., Prakash, A., Tripathi, R., 2021. In: Harvey, D., Kar, H., Verma, S., Bhaduria, V. (Eds.), A Survey on Proactive and Reactive Channel Switching Techniques in Cognitive Radios BT - Advances in VLSI, Communication, and Signal Processing. Springer, Singapore, pp. 719–729.

Wang, C., Chen, Y., Liu, K.J.R., 2017. Hidden Chinese restaurant game: grand information extraction for stochastic network learning. IEEE Trans. Signal Inf. Process. Over Networks 3 (2), 330–345.

Wang, J., Jiang, C., Zhang, H., Ren, Y., Chen, K.-C., Hanlo, L., 2020a. Thirty years of machine learning: the road to pareto-optimal wireless networks. IEEE Communications Surveys Tutorials 22 (3), 1472–1514.

Wang, N., Han, S., Lu, Y., Zhu, J., Xu, W., 2020b. Distributed energy efficiency optimization for multi-user cognitive radio networks over MIMO interference channels: a non-cooperative game approach. IEEE Access 8, 26701–26714.

Youssif, M.E., Nasim, S., Wasi, S., Khisal, U., Khan, A., 2018. Efficient cooperative spectrum detection in cognitive radio systems using wavelet fusion. In: International Conference on Computing, Electronic and Electrical Engineering.

Zhang, B., Chen, Y., Wang, C., Liu, K.J.R., 2012. Learning and decision making with negative externality for opportunistic spectrum access. In: 2012 IEEE Global Communications Conference (GLOBECOM), pp. 1404–1409.