



Research article

Evaluation of the performance of a collaborative proposal of multiple access in cognitive radio networks

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ABSTRACT

Cognitive radio networks (CRN) allow for an increase in spectral efficiency and performance of today's wireless networks. Currently, multiple proposals exist in the area of spectral decision-making and mobility; however, very few evaluate the impact of collaboration between secondary users and the performance of spectrum access by many secondary users. Unlike existing works, this article provides a comprehensive quantitative analysis of the performance of CRN taking into account access to the spectrum simultaneously by multiple users and decision making based on collaboration through the exchange of information between nearby secondary users. This proposal is developed through the implementation of four modules: Input Module, Multi-user Module, Collaborative module and Decision-making module, where the results are evaluated comparatively through the handoff rate generated with two multicriteria techniques: Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Multi-Criteria Optimization and Compromise Solution (VIKOR). The evaluation is carried out taking into account three levels of collaboration, three multi-user access scenarios, and two multi-criteria techniques for a total of 18 simulation scenarios. The results obtained show the importance of implementing collaboration strategies, as for multi-user access, the number of handoffs increases as the number of serial users increases. TOPSIS presented the best results in 76 % of the analyzed cases where VIKOR generated a smaller number of handoffs; TOPSIS maintained good performance with differences not exceeding 90 handoffs.

1. Introduction

1.1. General context

The growth of wireless applications poses challenges for future communications systems, according to Cisco. By 2023, more than 70 % of the world's population will have mobile connectivity, and total mobile data traffic is estimated to grow to 49 exabytes per month by 2021 (CISCO, 2021). Paradoxically, several extensive spectrum usage measurement campaigns have shown that some bands are overused (unlicensed bands) while other bands are underused (licensed bands) (Martínez Alonso et al., 2021).

The inefficient distribution of spectrum and the exponential growth of demand for wireless applications has become one of the main concerns of communications (Martínez Alonso et al., 2021). CR offers a set of

solutions by using spectrum dynamically, giving the communication system the ability to reconfigure itself based on the circumstances of congestion, traffic load, propagation of wireless channels, among others (Dinesh et al., 2021). The goal of CRN is for Secondary Users (SU) of unlicensed bands to operate on the licensed frequencies of Primary Users (PU) without causing harmful interference to the PU (Tayel et al., 2021). The process where an SU changes their operation frequency is called spectral mobility (Hernández-Suárez et al., 2016; Kumar et al., 2016) and gives way to a new type of CRN handoff called spectral handoff (Salgado et al., 2020).

In a communication system with dynamic assignment, the probability of two or more SU selecting the same channel is high, affecting positively or negatively the network performance. In addition, to perform an efficient decision-making process in CRN and to identify the PU signal, the SU must analyze the decisions made by other SU. The studied

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information will allow the SU to elaborate a description of the system state and improve the accuracy of decisions and, therefore, the efficiency of the network (Wang et al., 2017).

The SU decision-making process is currently a challenge in CRN (Gao et al., 2021; Jiang et al., 2014). Analyzing the decision-making process made by SU requires generating strategies to model networks under realistic parameters that analyze multi-user access and evaluate the effect of decisions made by an SU over the other SU, proposing strategies to exchange information collaboratively (Abbas et al., 2015).

In the context of CRN, collaborative strategies allow users to communicate with each other to exchange locally observed interference measurements. The goal is to take advantage of spatial diversity. To achieve this, the unlicensed user shares their detection information with neighboring users (Salgado et al., 2016; Thakur et al., 2017).

1.2. Contributions and Scope

This article proposes a decision-making model through the implementation of five modules: (1) Spectral Information Module, (2) Collaborative Module, (3) Multi-user Module, (4) Decision-making module, and (5) Performance Metrics Module. The first characterizes the behavior of PU through real spectral occupancy measurements. The second allows including multiple serial users. The third allows including collaborative strategies through the exchange of information between SU. The fourth contains the decision-making strategies used. The last module generates the performance metrics.

The contribution of this work is presented in four approaches. The first approach is the proposal and development of the collaborative information exchange and multi-user access modules. The second approach is the proposed communication between the multi-user module and the collective module, which allows analyzing the decisions made by an SU about the other SU when sharing information before accessing the spectrum. The third approach is the methodology evaluation, which implements a metrics module with two multi-criteria decision-making techniques: TOPSIS and VIKOR. The fourth approach is the unification of the actual behavior of the PU within the simulation environment carried out through spectral occupancy measurements in the GSM frequency band.

The goal is to analyze—in the same radio environment and simultaneously—the effect of exchanging information between SU and the usefulness of SU depends on the decisions made individually and the actions taken by other SU. The number of cumulative handoffs is used as performance metrics. The evaluation metric is obtained during the SU transmission time.

1.3. Application environments

From the research context, this work uses a methodology based on simulation processes, which allow the simultaneous analysis of the effect of exchanging information between SU and how the decisions of the SU affect the utility of the other SU. The results obtained present the behavior of the proposed strategy in a virtual simulation environment. However, as described in the "Contributions and Scope," the environment is based on actual PU behavior. This methodology allowed experimenting with real implementations and networks at a relatively lower cost and time than required.

This CRN decision-making strategy aims to improve the use of the radio spectrum. Apart from the research context in everyday situations, it promotes the competitiveness of a region, contributes to the life quality of the inhabitants, and generates social and economic development. From a social projection, the efficient and dynamic use of the radio environment increases coverage and improves the quality of service. The economic impact is a result of social development; therefore, there are several elements from which CRN contribute to economic growth, such as information networks for intelligent measurements and controls, electric mobility, health, industry, and services.

1.4. Literature review

Regarding previous research, no CR works were found that simultaneously analyzed spectral mobility, multi-user access, collaborative scenarios and decision-making. The works discussed in this document focus on relevant research associated with independent approaches and/or combinations of two of them.

Two works were identified in the area of decision-making and collaborative scenarios. Rodríguez-Colina et al. (2020) propose a collaborative model through a two-way information node with five levels of collaboration. The decision-making process is done through multi-criteria techniques implementing real data. The number of failed handoffs is used as a performance metric. According to the analysis of the implemented metrics, it is established that the collaboration level that leads to efficient results is between 20 % and 50 %. Ye et al. (2017) analyze the cost of interference for collaborative cognitive interference decision models. A tabu search-artificial bee colony algorithm is proposed for the decision-making process. To verify the robustness and capacity of the proposed algorithm, the number of iterations is analyzed based on the level of interference. The results obtained indicate that the proposed decision-making strategy has a higher probability of identifying the optimal decision scheme. The optimal criterion is given by the maximum interference effect employing a fast convergence speed.

In the area of decision-making and multi-user scenarios (M Almasri et al., 2019; Almasri et al., 2020) propose an All-Powerful Learning policy to solve decision-making problems with multiple users. The proposed policy considers priority access and multi-user dynamic access. SU should estimate and then access the best channels in terms of quality and availability. The proposed policy does not implement collaboration among users. The analysis of results allowed establishing that the implemented policy generated efficient results in the different users analyzed: dynamic users and priority users.

Two papers were identified in the area of multi-user scenarios and collaborative scenarios. Khedkar and Patil (2019) propose an intra-coalition and inter-coalition decision-making technique for a multi-user CRN. For spectrum allocation, the strategy used is Pareto optimal coalitions. Conventional decision-making metrics such as OR/AND/maximum voting/half voting rules are used. The results show a reduced workload and an increase in the speed of the decision process. Additionally, there are publications associated with the literature review. Rizk et al. (2018) present collaborative strategies for the decision-making process when implementing multi-agent structures or systems. Among the analyzed methods, probabilistic models and those based on meta-heuristic optimization techniques stand out. As a comparative strategy, the specific area of application and the optimality criterion is used.

1.5. Organization of the document

This work is organized and presented in five sections. Section 2 describes the methodology and the characteristics of the five modules implemented. This section also presents the adjustments of the proposed modules and the validation and evaluation structure used. Section 3 presents the performance metrics obtained for each scenario analyzed and includes the quantitative analysis of the results with the respective discussion. Section 4 presents the general conclusions obtained. Finally, section 5 suggests future work.

2. Materials and methods

This article proposes a decision-making model through the implementation of five modules: Spectral Information Module, Multi-user Module, Collaborative module, Decision-making module and Performance Metrics Module. The goal is to analyze—in the same radio environment and simultaneously—the effect of exchanging information between SU and how SU decisions affect the utility of the other SU. The following is the methodological description and adjustments assigned to

the modules developed for the decision-making analysis in collaborative and multi-user environments.

2.1. Proposed model

Figure 1 displays the block diagram of the proposed model for the decision-making process through collaborative information exchange and multi-user access. As can be seen, the design operates under a five-module architecture: (1) Spectral Information Module (2) Collaborative Module (3) Multi-user Module (4) Decision-making module (requires a search algorithm for spectral mobility analysis), and (5) Performance Metrics Module. Table 1 presents an overview of each of the modules.

The proposed strategy allows two types of communication with the decision-making module. The first communication is through the multi-user module; this connection is made when there are multiple SU. If there are not different users, the second communication is a direct connection with the collaborative module. This scenario does not include the multi-user module. This communication allows to analysis only the exchange of information between SU.

Each of the modules of the proposed model is described in detail. In section 2.2 Spectral Information Module, in section 2.3 Collaborative Module, in section 2.4 Multi-User Module, in section 2.5 Decision-Making Module, in section 2.6 Performance Metrics Module. Finally,

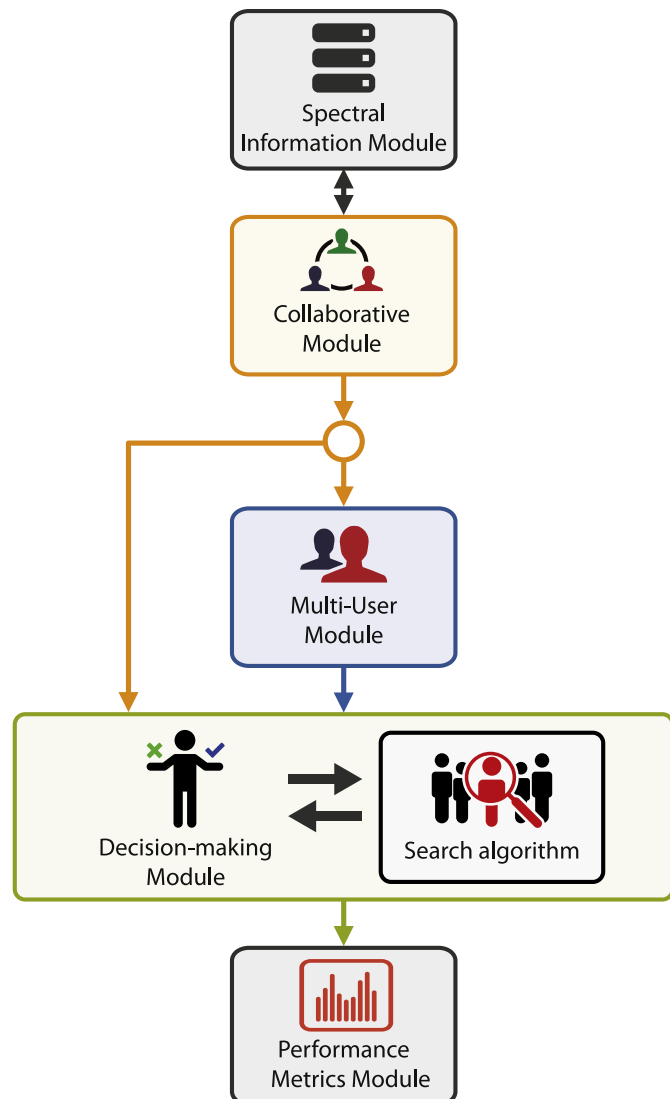


Figure 1. Implemented structure architecture.

and considering that several configurations can be assigned to each module, section 2.7 presents the settings referred to each module and the respective scenarios for validation and analysis of the proposed strategy.

2.2. Spectral information module

The related literature uses mathematical traffic models based on random estimations (Camelo et al., 2020; Han et al., 2020) however, although they are detailed traffic models, they do not present evidence of their performance under actual PU behaviors. The model proposed in this research incorporates actual PU behavior within the simulation environment through solid spectral occupancy measurements in the GSM frequency band (824–874 MHz).

The spectral information that includes the actual behavior of the PU is built through two stages: the first one performs the spectral power measurement process. The second one generates the availability of the radio environment according to a threshold level. Additionally, in the second stage, the availability information is processed twice: the first one characterizes the traffic according to the level of opportunities; the second one selects the information to be used for training and validation of the decision-making techniques.

Spectral Information Module contains the information of the spectral power of the measured radio environment; it generates the availability information according to the Threshold level. Finally, it performs the two processes to the availability information. A detailed description of each of the stages is presented below.

2.2.1. Spectral occupancy measurement

The measurement of spectral occupancy is performed using the energy detection technique; this technique was selected because of the low computational burden and its simple implementation (Ali and Hamouda, 2017; Nallagonda et al., 2021; Youssef et al., 2018). The equipment used is a Discone antenna with a frequency range between 25 MHz to 6 GHz, a Low Noise Amplifier with a frequency range between 20 MHz to 8 GHz, and a spectrum analyzer with a frequency range between 9 kHz to 7.1 GHz. The measurement ranges were based on sweep time, bandwidth resolution, and Span. A power threshold of 5 dBm, a protection level of +5 dBm, and an average noise floor of -113 dBm were used to minimize the probability of false alarm; likewise, the decision threshold was set at -113 dBm +5 dBm = -108 dBm (Hernández-Suárez et al., 2016). Pedraza et al. (2016) Chapter three presents a more detailed explanation of the configuration of the technical parameters of the spectrum analyzer. Figure 2 describes the measurement structure used, the equipment, and the respective characteristics. Table 2 describes the technical parameters of the measurement performed.

According to the measurement period and the sweep time value adjusted to 290 ms guarantee the detection of GSM signals (Pedraza et al., 2014), it built a database with 4,468,608,000 data. A power matrix of 500 columns and 8,937,216 rows represents the database, where the columns represent the frequencies or channels, and the rows represent the time in seconds.

2.2.2. Availability of the radio environment

The spectral availability information is required to implement the decision-making process through collaborative information exchange and multi-user access. A decision threshold is implemented to obtain channel availability information; there is no single criterion for the decision threshold selection. One of the biggest challenges to implement an energy detector is to choose the threshold (Lipski et al., 2021). A constant threshold is used in most conventional methods to detect the presence or absence of a PU signal. This PU signal can be determined from different strategies, such as the trade-off between detection probability and false alarm probability, binary assumptions using Gaussian distributions for Noise Floor signal, desired detection probability, mean and standard deviation of the whole received signal (Verma, 2020). A threshold level of -95 dBm is used as a criterion selected regarding the balance search

Table 1. Description of the modules.

Module	Description
Spectral Information	Characterizes the radio environment through the behavior of the PU.
Collaborative	It acts as a source of information and as a relay; it is a bidirectional information structure that allows users to communicate to exchange measurements.
Multi-User	It allows including multiple serial users in the simulation environment.
Decision-making	Parameterizes the structure of decision-making models. Additionally, this module has a search algorithm in charge of quantifying the number of spectral handoffs.
Performance Metrics	It takes the information from the spectral decision module and generates the performance metrics.

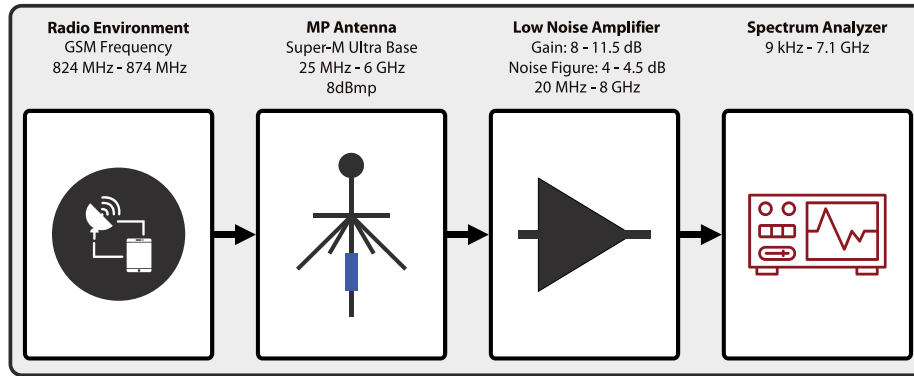


Figure 2. Structure for spectral occupancy measurement.

Table 2. Parameters for spectral occupancy measurement.

Parameter	Value
Measurement characteristics	Sweep time
	Bandwidth Resolution
	Span
Sweep time	290 ms
Bandwidth Resolution	100 kHz
Span	50 MHz
Frequency band	GSM (824 MHz–874 MHz)
Number of channels	500
Detection technique	Energy detection
Measurement period	1 month

between the detection probability and the false alarm probability (Dig- ham et al., 2007; Lehtomaki et al., 2005; Pedraza, 2016). Channels with lower powers than the decision threshold value are classified as available represented in the availability matrix as a logical one (1). In the opposite case, channels with higher powers than the decision threshold value are classified as occupied represented in the availability matrix as a logical zero (0) (Pedraza et al., 2016). From the spectral availability matrix and to extract relevant information for the proposed applied strategy, two processes are performed; the first one determines the traffic level. The second one generates the matrices for the training and validation of the decision-making techniques.

To characterize the traffic level is used the availability probability (AP), a parameter obtained by calculating the average of each of the columns of the availability matrix. A high traffic level indicates a low number of spectral opportunities, and a low traffic level indicates a high number of spectral conveniences. As part of the design criteria, an 80 % AP was selected for low traffic and a 20 % AP for long traffic.

Due to the type of decision-making technique to be implemented and based on the cross-validation methodology, it is required to identify a data set with a matrix structure for training and validation. The training matrix, which allows configuring the initial parameters of the algorithms, is the one used for the collaborative analysis, contains the spectral occupancy information of an hour. The evaluation matrix, used to obtain

the results of the evaluation metrics of the implemented algorithms, contains the spectral occupancy information of nine minutes. As a design criterion, it was selected a cross-validation ratio of 70-30. 70 % of the data is used for training, and 30 % of the info is used for validation.

Figure 3 represents the second stage of the spectral information module as previously described. In this stage, the availability matrix is obtained through the threshold level. The size of the availability matrix is equivalent to that of the power matrix, 500 columns and 8,937,216 rows, where the columns represent the frequencies or channels and the rows represent the time in seconds. Additionally, the availability matrix is characterized according to the traffic level. Also, it generates the data for training and validation.

2.3. Collaborative module

The second module allows including collaborative decision-making processes through the exchange of information between SU. In (Giral et al., 2020) the structure of the developed collaborative module is described in detail. This module, as shown in Figure 1, is connected to the Spectral Information Module. Its function is to share and retransmit information; it is a bidirectional structure that analyzes the effect of exchanging information between SU. The general idea is to segment the input matrix into submatrices and characterize levels of collaboration according to the percentage of information to be shared. Each sub-matrix represents a collaborative SU and collaboration levels are chosen according to data limits: 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 %, and 100 %, where 10 % and 100 % correspond to the criterion of too little or too much data respectively.

Figure 4 presents the structure of the collaborative module. As input variable, the training power matrix is required. The number of users (*User 1, User 2, User 3, ..., User n*) is adjusted according to the “Collaborative SU Number” parameter, and “Division” sets the methodology for splitting. As shown in Figure 4, for a division by column (*Division = Column*), if the number of users is greater than or equal to ten (*Collaborative SU Number ≥ 10*), the columns of the power matrix are divided into 10 equal parts and the rows are divided into *m* parts until completing the number of users (*Total Users = 10(m)*). If the number of users is less than 10 (*Collaborative SU Number < 10*), the rows of the power matrix are divided into 2 equal

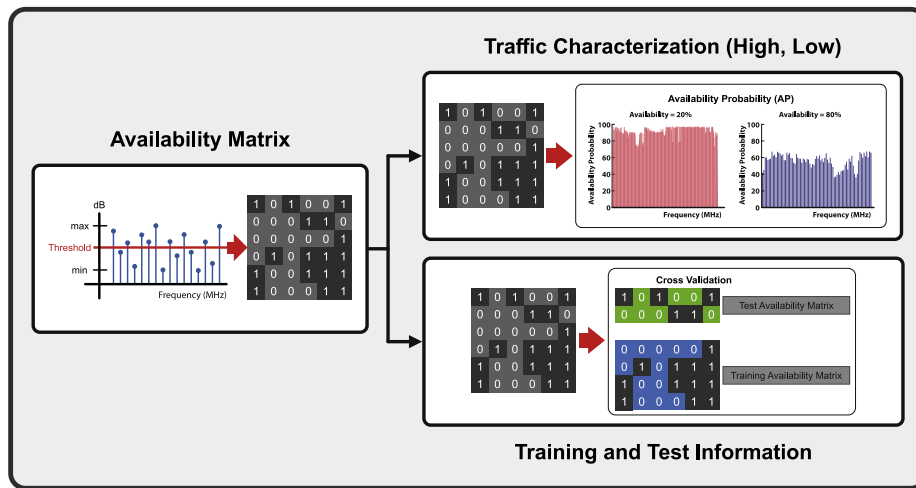


Figure 3. Activities for the availability of the radio environment.

parts and the columns are divided into m parts until completing the number of users ($Total\ Users = 2(m)$).

To establish the information to be shared between SU, it is necessary to establish the segmentation methodology and the levels of collaboration. As shown in Figure 4, of the total number of users ($User\ 1, User\ 2, User\ 3, \dots, User\ n$) is randomly selected ($Segmentation = Random\ Zone$) $K\%$ of users ($Users\ Percentage = K\%$). This $K\%$ of users represents—in addition to the information to be shared—the percentage of users who will participate in the training of the respective decision-making models.

A particular description omitting the segmentation type and the division method is presented in Figure 5. The input information (Database) is taken and divided into n submatrices ($Collaborative\ SU\ Number = n$). After the division into submatrices, the amount of information to share in the training is selected according to the collaboration level (Percentage). According to Figure 5, for a total number of users equal to four ($n = 4$), a 25% collaboration level ($Percentage = 25\%$) corresponds to a training based on the information of a single user ($Collaborative\ Users = 1$), a 50%

collaboration level ($Percentage = 50\%$) corresponds to a training based on the information of two users ($Collaborative\ Users = 2$), a 75% collaboration level ($Percentage = 75\%$) corresponds to a training based on the information of three users ($Collaborative\ Users = 3$), and if the level is 100% ($Percentage = 100\%$), the training uses all available information ($Collaborative\ Users = 100$).

2.4. Multi-user module

Designing efficient multi-user access networks is a challenge for next-generation wireless communication systems. In CRN, the utility of SU depends on decisions made individually and actions taken by other SU. In a dynamic allocation system with multiple user access, the probability of two or more SU selecting the same channel, positively or negatively affecting network performance, is high (Abbas et al., 2015). This module incorporates in the decision-making process a real feature of a wireless network; this feature consists of including in the simulation environment

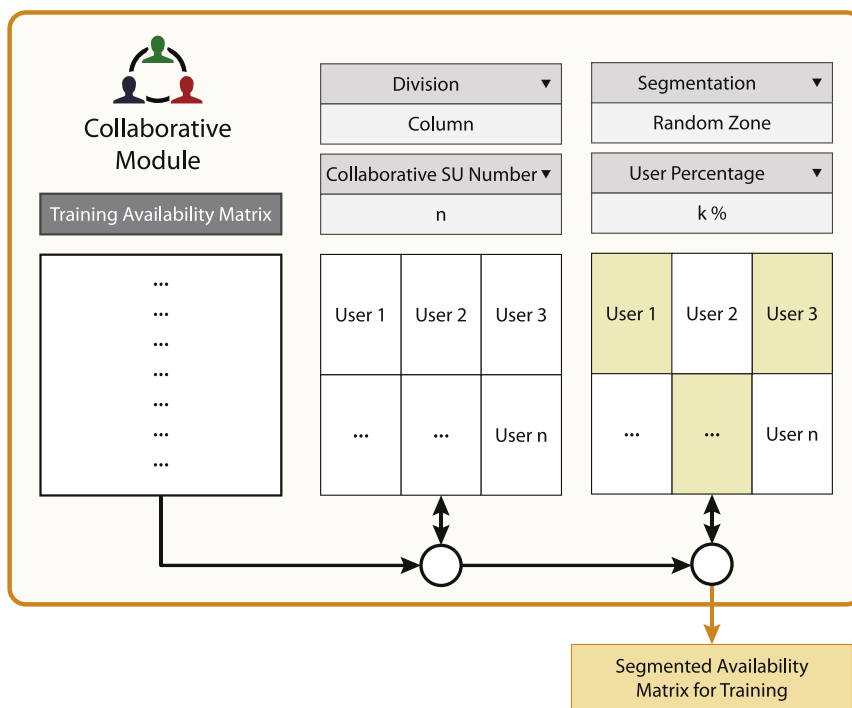


Figure 4. General diagram of the collaborative module.

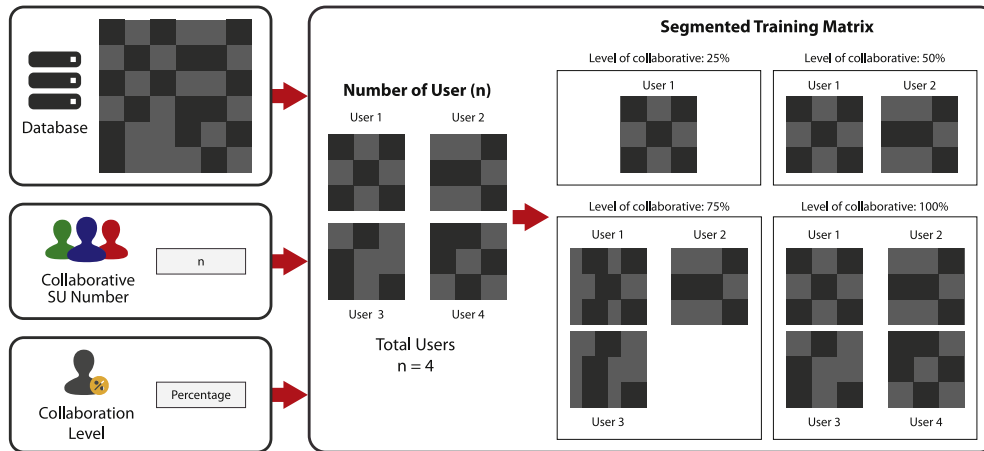


Figure 5. Particular operation of the collaborative model.

multiple users with serial access to subsequently analyze how the decisions of the SU affect the utility of the other SU. As shown in Figure 1, this module is a communication node between the collaborative module and the decision-making module; communication that will be active if the scenario to be analyzed includes the access of multiple users. For the decision-making process, the module allows SU to share information before accessing the spectrum. The exchange of information after the decision is made is not taken into account. Giral et al. (2021b) describes the structure of the developed multi-user module in detail.

Figure 6 presents the structure of the multi-user module. As an input parameter, only the number of serial users or conventional users is required, with a maximum availability of 30 users. The module includes a structure called “Real Mode”; it is a feature that assigns to the simulation a real event of a wireless communication system. This structure introduces a set of random users between one and the maximum value of serial users, with no interest in analysis, that appear at random times and that will not be present the entire simulation time (ST). The total number of users in the simulation corresponds to the number of serial users adjusted to the input plus the number of random users. The following sections describes the “Real Mode” structure in detail.

2.4.1. Simulation mode: real mode

In addition to the multiple users generated by the module, this simulation mode allows random behaviors in terms of quantity, time, and location to be incorporated into the simulation environment. In a wireless communication system, during transmission time, users are constantly entering and leaving randomly. This user behavior alters the radio environment and therefore needs to be included in the simulation process. In the real simulation mode, random users are included, who enter and leave at random times. Thus, users will not be present during the whole ST. Additionally, as the access is serial, random users are randomly placed among the conventional users.

The number of random users: As described in Figure 6, the number of “Serial Users” corresponds to the sum between the NSU set in the module and the number of randomly generated users. Using a uniform probability distribution, it was possible to define the number of random users bounded by a minimum value of 1 user and a maximum value equal to the NSU. This interval was assigned to have at least one random user during the ST and that the number of random users never exceeds the NSU.

Random users transmission time: A percentage range is defined as a function of the ST to establish the participation time of a random user in the spectral decision process. A random user will only be able to enter when 30 % of the ST is exceeded and will be part of the process up to a maximum of 70 % of the ST. This interval was assigned to differentiate random users from conventional users; if a random user remains 100 % of the ST, his behavior would be that of a conventional user.

Location of random users: After defining the number of random users and the time they enter and leave the ST; it is necessary to establish the random users’ location according to the conventional users. Figure 7 describes the methodology used, taking into account that the multi-user access of the proposed module is serial; the random users can be located between two conventional users, in an initial position or an end position. As well as the number of users and time, the location is developed through a random structure.

2.5. Decision-making module

The challenges of the decision-making process for next-generation wireless networks are diverse. The ongoing task is to identify efficient methods with low computational burdens. Multi-criteria decision-making techniques (MCDM) provide a set of alternatives from a generally discrete solution space. Decision-making strategies using MCD were selected because they are a mathematical method widely used in

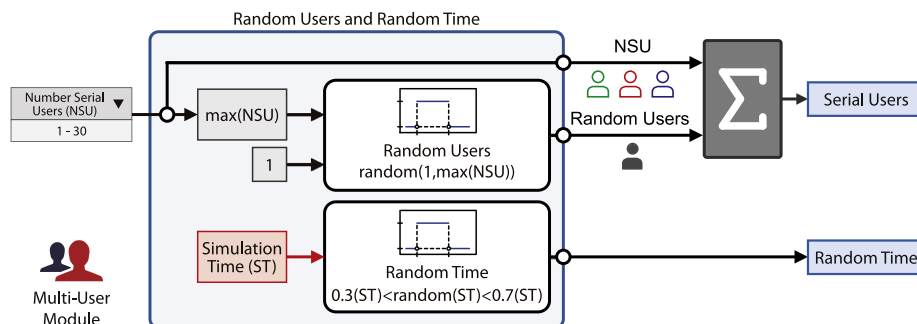


Figure 6. General diagram of the multi-user module.

decision-making processes (Awathankar et al., 2021; Deveci et al., 2021; Jayakumar et al., 2019). To implement MCDM, decision vectors and weight-based attributes are required as input parameters. Decision vectors are obtained through statistical processes and the weights are assigned according to the decision criteria (Erdogan et al., 2019; Kou et al., 2021).

Figure 8 describes the decision-making process implemented in this work. The first block named Information Processing requires information from the Spectral Information Module (Test Availability Matrix) and the collaborative module (Segmented Availability Matrix for Training), is responsible for calculating the decision vectors: AP, AAT, ASINR, and ABW, Table 3 presents the acronym, meaning, and description of the decision vectors (Giral et al., 2021a). Páez et al. (2017) describes the methodology used to determine the decision vectors. The second block called Decision-making, in addition to decision vector information, uses the weights of multicriteria techniques as input information. It is in charge of calculating the Ranking vector, which has the information on the positions of the channels according to the best scores. These positions are obtained according to the MCDM used. The information in the multi-user module is used for mobility analysis: a process that is performed through the search algorithm and is part of the decision-making block. Finally, the spectral mobility information is delivered to the Performance Metrics Module to generate performance metrics.

2.5.1. MCDM algorithm

The block determines the score of the channels from Eq. (1). It uses the decision vectors (AP, AAT, ASINR, ABW), the weights according to the decision criteria (W_{AP} , W_{AAT} , W_{ASINR} , W_{ABW}), and the MCDM to be implemented. Eq. (1) assigns the score to each spectrum channel and the MCDM establishes the best channels with the highest number of spectral opportunities. The location is stored in a vector called Ranking. The channel with the best evaluation is the one selected for transmitting the SU data. If the channel is busy, a channel change is made according to the next best evaluation (Rodríguez-Colina et al., 2020).

$$Score = W_{AP}(AP) + W_{AAT}(AAT) + W_{ASINR}(ASINR) + W_{ABW}(ABW) \quad (1)$$

To carry out a comparative evaluation, two MCDM are implemented: TOPSIS and VIKOR. This selection was made because of the excellent results that these techniques have presented in decision-making processes for CRN (Divya & Nandakumar, 2019; Giral et al., 2021a, 2021b; Loganathan et al., 2020; Rathee et al., 2019; Rodríguez-Colina et al., 2020; Sofuoğlu, 2021; Sumith et al., 2018).

Initially, it constructs the decision matrix x . This matrix represents the product between the decision vectors (AP, AAT, ASINR, ABW) and the decision criteria (W_{AP} , W_{AAT} , W_{ASINR} , W_{ABW}). Next, it presents the mathematical model that allows obtaining the information of the channel positions according to the best scores using the VIKOR and TOPSIS MCDM. As a decision matrix, the matrix Eq. (2) is used, where $\omega_1, \dots, \omega_n$ represent the decision criteria and $\bar{x}_{1,1}, \dots, \bar{x}_{N,M}$ describes the decision vectors.

$$x = \begin{pmatrix} W_1 \bar{x}_{11} & \dots & W_M \bar{x}_{1M} \\ \vdots & \ddots & \vdots \\ W_1 \bar{x}_{N1} & \dots & W_M \bar{x}_{NM} \end{pmatrix} \quad (2)$$

2.5.1.1. Multi-Criteria Optimization and Compromise Solution (VIKOR). (Opricovic, 1998) proposes the VIKOR method. It focuses on ranking and selecting a set of alternatives in the presence of conflicting criteria. It introduces the multi-criteria ranking index based on the particular closeness measure to the ideal solution (Opricovic and Tzeng, 2004). VIKOR was developed to achieve optimization of complex systems with multiple criteria. The algorithm follows the steps described in (Golfam et al., 2019; Hashemi et al., 2021; Meng et al., 2021).

For each parameter $j = 1, 2, 3, \dots, N$ of Eq. (2), the maximum and smallest value of each column is determined through Eqs. (3) and (4). Where N_b is the set of profit parameters, F_j^+ is the best value of criterion j y F_j^- is the worst value of criterion j .

$$F_j^+ = \left\{ \left(\max_{i \in M} x_{ij} \mid j \in N_b \right) \right\} \quad (3)$$

$$F_j^- = \left\{ \left(\min_{i \in M} x_{ij} \mid j \in N_b \right) \right\} \quad (4)$$

The VIKOR method defines a normalized distance S_i ; this distance represents the maximum utility for the decision-making process, S_i is determined through Eq. (5). Where $i = 1, 2, 3, \dots, M$.

$$S_i = \sum_{j \in N} w_j \frac{(F_j^+ - x_{ij})}{(F_j^+ - F_j^-)} \quad (5)$$

The minimum and maximum values of the normalized distance defined by Eq. (5) are denoted by S^+ , S^- . Where S^+ , S^- are obtained as

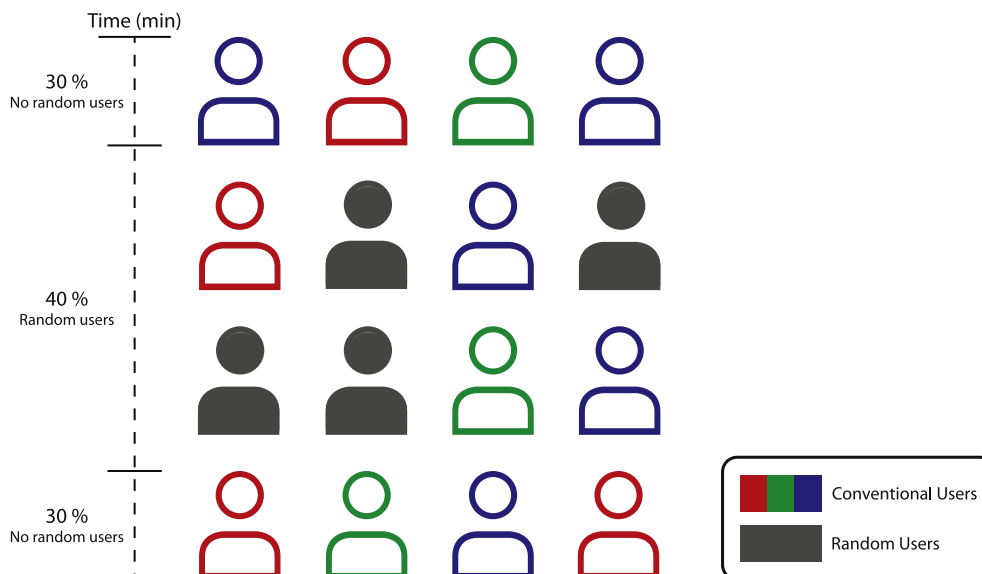


Figure 7. Random user location.

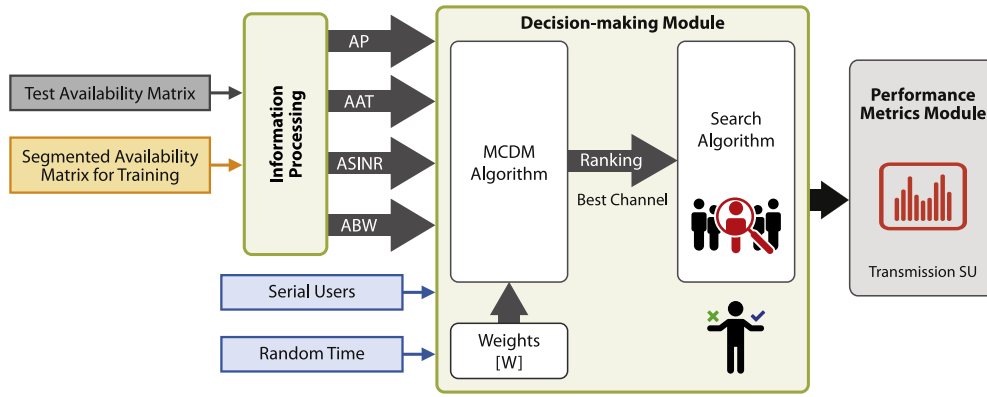


Figure 8. Structure of decision-making models using multi-criteria techniques.

Table 3. Description of decision vectors for multi-criteria analysis.

Acronyms	Meaning	Description
AP	Availability Probability	Average of each of the columns of the availability matrix.
AAT	Average Availability Time	Average of consecutive ones of the availability matrix.
ASINR	Average Signal-to-Interference-Plus-Noise Ratio (SINR)	Average of each column of the SINR matrix without taking into account zeros.
ABW	Average Bandwidth	Average of each of the columns of the bandwidth matrix.

profit parameters according to Eq. (6). S^+ , S^- , represent the minimum and maximum values respectively of each of the S_i columns.

$$\begin{aligned} S^+ &= \min_{i \in M} S_i \\ S^- &= \max_{i \in M} S_i \end{aligned} \quad (6)$$

The VIKOR method defines an individual normalized distance R_i determined by the Eq. (7).

$$R_i = \max_{i \in N} \left[w_j \frac{(F_j^+ - x_{ij})}{(F_j^+ - F_j^-)} \right] \quad (7)$$

The minimum and maximum values of the individual normalized distance defined by Eq. (7) are denoted by R^+ , R^- . Where R^+ , R^- are obtained as profit parameters according to Eq. (8). R^+ , R^- , represent the minimum and maximum values respectively of each of the columns of R_i .

$$\begin{aligned} R^+ &= \min_{i \in M} R_i \\ R^- &= \max_{i \in M} R_i \end{aligned} \quad (8)$$

Based on S_i and R_i the VIKOR index is determined, which is denoted by Q_i and is determined according to Eq. (9). Where γ is a weighting reference, it represents the maximum utility strategy and varies in the interval [0, 1].

$$Q_i = \gamma \left(\frac{S_i - S^+}{S^- - S^+} \right) + (1 - \gamma) \left(\frac{R_i - R^+}{R^- - R^+} \right), \quad 0 \leq \gamma \leq 1 \quad (9)$$

Given the values of Q for all i belonging to M , the candidate channels are rank from highest to lowest. Finally, the selected carriers (A_{VIKOR}) are given by the optimal Q , as described in Eq. (10).

$$A_{VIKOR} = \operatorname{argmin}_{i \in M} Q_i \quad (10)$$

2.5.1.2. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The TOPSIS method was proposed in (Chen and Hwang, 1992), alluding to (Hwang and Yoon, 1981) work based on the Euclidean distance (Awathankar et al., 2021; Loganathan et al., 2016). The solution is a point in space with the shortest Euclidean distance from the positive

ideal solution and the longest Euclidean distance from the negative optimal solution (Zhang and Pan, 2021). The algorithm follows the steps described in (Meng et al., 2021; Moosivand et al., 2021).

The first step is to normalize the decision vectors to obtain the weighted normalized scores for Eq. (2). Subsequently, for each parameter $j = 1, 2, 3, \dots, N$ of Eq. (2). The positive ideal solutions (A^+) and the adverse ideal solutions (A^-) are identified by Eqs. (11) and (12). Where A^+ and A^- are the set of benefits.

$$\begin{aligned} A^+ &= \{(\max x_{ij} | j = 1, 2, \dots, N)\} \\ A^+ &= \{x_1^+, \dots, x_M^+\} \end{aligned} \quad (11)$$

$$\begin{aligned} A^- &= \{(\min x_{ij} | j = 1, 2, \dots, N)\} \\ A^- &= \{x_1^-, \dots, x_M^-\} \end{aligned} \quad (12)$$

For each alternative is obtained the Euclidean distance D , the distances to the best (D^+), and the worst difference (D^-) are calculated using Eqs. (13) and (14).

$$D_i^+ = \sqrt{\sum_{j=1}^M (x_{ij} - A_j^+)^2} \quad (13)$$

$$D_i^- = \sqrt{\sum_{j=1}^M (x_{ij} - A_j^-)^2} \quad (14)$$

Finally, Eq. (15) calculates the relative closeness to the ideal solution C_i . The result obtained corresponds to the alternatives arranged in descending order.

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-} \quad (15)$$

2.5.2. Search algorithm

To perform the spectral mobility study a search algorithm is carried out. This algorithm employs a position vector as an input parameter, obtained through the decision-making models. In the first elements of the vector, the channels or frequencies with the highest number of spectral opportunities are located; in the last elements of the vector the channels

or frequencies with the lowest number of spectral opportunities are located. The vector of input information is called Ranking.

Likewise, it is called a search algorithm because it is in charge of searching the availability matrix for available channels. Channel changes are made based on the elements of the Ranking vector. When finding an available channel, the search algorithm performs a row change (time instant) in the availability matrix. To analyze the spectral mobility and, therefore, the efficiency of the decision-making strategy implemented, is used the information of the channel changes performed for each instant.

The process is equivalent for multiple users; the difference is in the condition for the row change. The algorithm may encounter two scenarios. The first scenario occurs when the number of spectral opportunities is greater than or equal to the users' requirements. In this scenario the queue changes when all users encounter spectral opportunities. The second scenario occurs when the number of spectral possibilities is less than the users' requirements. In this scenario, it is not possible to find all the opportunities. Therefore, the search algorithm stores the event and performs the queue change to start the search again at the next instant.

Figure 9 presents the two scenarios described above. Four users are presented, three of them are conventional serial users and one is randomly generated according to the characteristics of the "real mode". As identified in the figure, the random user is between the second and third conventional users. The search algorithm uses the Ranking position vector to spot the spectral possibilities, where the number {1} in this vector represents the channel with the highest probability of availability, the number {7} in this vector shows the canal with the lowest availability possibility.

In the first scenario of Figure 9, User 1 finds spectral opportunity in the Ranking vector position {1}. User 2 notices spectral opportunity in the location of the Ranking vector position {4}. It is not possible to hold the position {2} or {3} because the channels are covered by the PU. Additionally, the algorithm does not perform the search in the canal {1}, after the assignment made to User 1, the algorithm is fed back and informs that this channel is no longer available. This search and feedback logic is applied for the other users, User Random finds spectral opportunity in the Ranking vector position {6} and User 3 identifies a spectral opportunity in the Ranking vector position {9}. As all users find spectral opportunities, the algorithm performs a row skip and starts the search again. As the number of spectral possibilities is greater than the users' requirements, the algorithm switches row and sets up the search analysis again.

In the second scenario of Figure 9, the number of spectral opportunities is less than the user requirements. User 1 and User 2 find availability in the Ranking vector position {5} and {9} respectively. For this

scenario, once finished the search, the algorithm reports the event, switches ranks, and starts again.

2.6. Performance Metrics Module

The cumulative number of spectral handovers obtained during the transmission time or ST of the SU is used as a performance metric to analyze the proposed strategy through the five developed modules. This metric is associated with spectral mobility and allows quantifying the channel shift of the SU (Hernandez et al., 2020a, 2020b). A spectral handover in CRN occurs when an SU must change its channel to continue its communication in another spectral opportunity. This process is a fundamental aspect to guarantee an adequate quality of service and improve communication performance (I F Akyildiz et al., 2008; Ian F Akyildiz et al., 2006; Lam et al., 2013).

During a spectral handoff, it is inevitable that communication will break temporarily, so it turns out to be a key aspect in CRN performance. The spectral decision plays a very important role in improving this performance (Hernández et al., 2016; López et al., 2015; Oyewobi and Hancke, 2017; Páez et al., 2017).

2.7. Adjustment of the proposed modules

The validation of the proposed model for the decision-making process through collaborative information exchange and multi-user access is performed by communicating the decision-making module with the collective module through the multi-user module (Figure 1). This communication is selected to analyze the information exchange between the SU when there are multiple SU. As described in the previous sections, each module has different configuration parameters. The settings assigned to each module are described below. It is important to note that when working with all modules simultaneously, the combinations are diverse. There is no optimal configuration; the settings assigned to each module depending on the scenario to be analyzed.

2.7.1. Spectral information module

Through the spectral occupancy measurements, this module incorporates the actual behavior of the PU within the environment simulation. The only available setting is the ST, which is associated with the number of rows of the evaluation matrix and corresponds to the number of applicable changes per row (instantaneous time) performed by the search algorithm. The evaluation matrix contains the spectral occupancy information for nine minutes; therefore, it can be parameterized in the

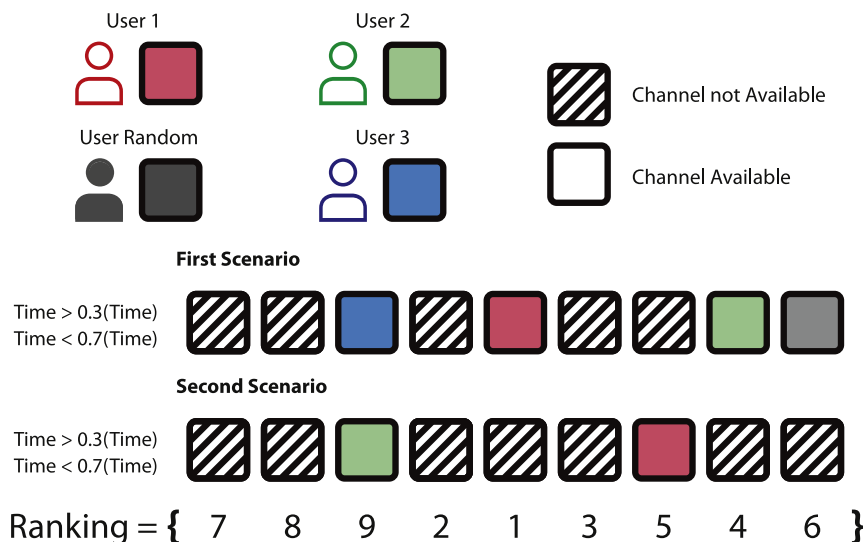


Figure 9. Spectral mobility scenarios for the search algorithm.

range of 1 min–9 min. This research holds the value of 9 min. The metric used is cumulative; therefore, using the maximum time value allowed analyzing the behavior of the strategy in the total minutes available.

2.7.2. Collaborative module

Table 4 describes the settings of the collaborative module in terms of the number of collective users, splitting, and segmentation. For this research, the assigned environments are according to the level of collaboration that presents the most efficient results. This level can be parameterized between 10 % and 100 % (Giral et al., 2020) address this feature in their work, where the authors showed that the range for the collaboration level with the best results is between 20 % and 50 %. As an additional element, this paper analyzed a level of collaboration outside this range.

2.7.3. Multi-user module

There is no optimal or good configuration for the number of serial users in the simulation environment. This parameter is associated with actual behaviors of wireless communication systems, where users permanently enter and leave at random times. Therefore, the adjustment of the number of serial users depends on the scenario to be analyzed. This work studies the consequences for the decision-making process when including multiple SU; therefore, it is necessary to implement plots where a low, medium and a high number of serial users are present. As described, for the low-serial user scenario, the item was set in the range of 1 SU to 3 SU. For the intermediate serial user scenario, the section was laid in the length of 1 SU to 6 SU. And, for the high serial user scenario, the segment was headed in the area of 1 SU to 9 SU. The module was not selected for two elements even though it can implement a value greater than 9 SU. The first is the computational load required to include more SU. The second is because it reduces the quality of the figures used for the metrics analysis.

2.7.4. Decision-making module

For the comparative analysis are used VIKOR and TOPSIS. According to the mathematical model of each of the techniques are implemented the algorithms. Figure 8 describes the input parameters correspond to the decision vectors and the weights according to the decision criteria. The Information Processing block calculated the decision vectors according to the respective mathematical equivalents (Páez et al., 2017). Therefore, the only configuration required is the size of the training availability matrix, done in the Collaborative Module.

The weights according to the decision criteria (W_{AP} , W_{AAT} , W_{ASINR} , W_{ABW}), if adjusted in this module, are determined using the Delphi method. This method is implemented because of its simple structure, and it also has been embraced in several applications, such as forecasting, estimation, and decision-making problems (Green et al., 2007; Jiménez-Rodríguez et al., 2020; Nurwarsito and Iskandar, 2021). Jiménez-Rodríguez et al. (2020) state that it is an effective technique that provides feedback of information contributions and evaluation of judgments. The method consists of a panel of experts answering interviews, professionals immersed in network management and operation verifying whether the criteria and factors are sufficient (Cho and Lee, 2013; Hernandez et al., 2015). For the decision-making analysis implemented in this research were used the weights described in (Hernandez et al., 2015). Eq. (16) displays these weights.

$$Score = 0.3593(AP) + 0.2966(AAT) + 0.1970(ASINR) + 0.1471(ABW) \tag{16}$$

2.7.5. Validation and analysis of the proposed strategy

The results are structured from three comparative analyses. Table 5 presents the respective scenarios selected according to the previously described configurations, for a total of 18 scenarios. Based on the scenarios, three comparative evaluations are established. The first analysis establishes the handoff number; the second compares the number of total handoffs obtained in minute nine. Finally, the third analysis compares the total number of handoffs obtained in minute nine according to the MCDM.

3. Results and discussion

This section presents and analyzes the results obtained from the proposed model for the decision-making process through collaborative information exchange and multi-user access. MATLAB – MathWorks version R2021a was used as a simulation tool; the hardware corresponds to a 2.8 GHz Intel (R) Core (TM) i7-7700HQ processor with a 24 GB RAM. Sections 3.1, 3.2, and 3.3 present the results obtained by implementing the proposed decision-making model, using the scenarios in Table 5 and through the performance metrics described in section 2.6. Section 3.4 represents the quantitative discussion of the results obtained.

3.1. Handoffs number for three multi-user structures and three levels of collaboration

Figure 10 presents the handoffs number obtained when the TOPSIS decision-making model was implemented with a 20 % collaboration level. Figure 10 (a), Figure 10 (b) and Figure 10 (c) correspond to multi-user access scenarios of 3 SU, 6 SU, and 9 SU respectively. In general, for all three scenarios, during the nine minutes of transmission, the lowest number of handoffs with the best performance was for 1 SU, with the exception of the 3 SU scenario where the best performance was for 2 SU access. The highest handoff value, i.e., the lowest performance, occurred for the access with the highest number of users.

Figure 11 presents the handoffs number obtained when the TOPSIS decision-making model was implemented, with a 40 % collaboration level for Figure 11 (a) and an 80 % collaboration level for Figure 11 (b). Each figure contains three multi-user access scenarios that correspond to 3 SU, 6 SU, and 9 SU.

Figure 12 presents the handoffs number obtained when implementing the VIKOR decision-making model with a 20 % collaboration level. Figure 12 (a), Figure 12 (b) and Figure 12 (c) correspond to multi-user access scenarios of 3 SU, 6 SU and 9 SU respectively. In general, for all three scenarios, during the nine minutes of transmission, the lowest number of handoffs with the best performance was 1 SU. The highest handoff value, i.e., the lowest achievement, was for the access with the highest number of users.

Figure 13 presents the handoffs number obtained when the TOPSIS decision-making model was implemented, with a 40 % collaboration level for Figure 13 (a) and an 80 % collaboration level for Figure 13 (b). Each figure contains three multi-user access scenarios that correspond to 3 SU, 6 SU, and 9 SU.

Table 4. Collaborative module adjustments.

Input data	Training Availability Matrix	
Number SU Collaborative	100	
User relation	Division	Column
	Collaboration Level	20 % – 40 % – 80 %
	Segmentation	Random

Table 5. Scenarios comparative analysis.

ST	Collaboration Level	Multi-user Access	MCDM
9 min	20 % – 40 % – 80 %	1 SU – 2 SU – 3SU	TOPSIS
		1 SU – 2 SU – 3SU – 4 SU – 5 SU – 6SU	
		1 SU – 2 SU – 3SU – 4 SU – 5 SU – 6 SU – 7 SU – 8 SU – 9 SU	
	20 % – 40 % – 80 %	1 SU – 2 SU – 3SU	VIKOR
		1 SU – 2 SU – 3 SU – 4 SU – 5 SU – 6SU	
		1 SU – 2 SU – 3 SU – 4 SU – 5 SU – 6 SU – 7 SU – 8 SU – 9 SU	

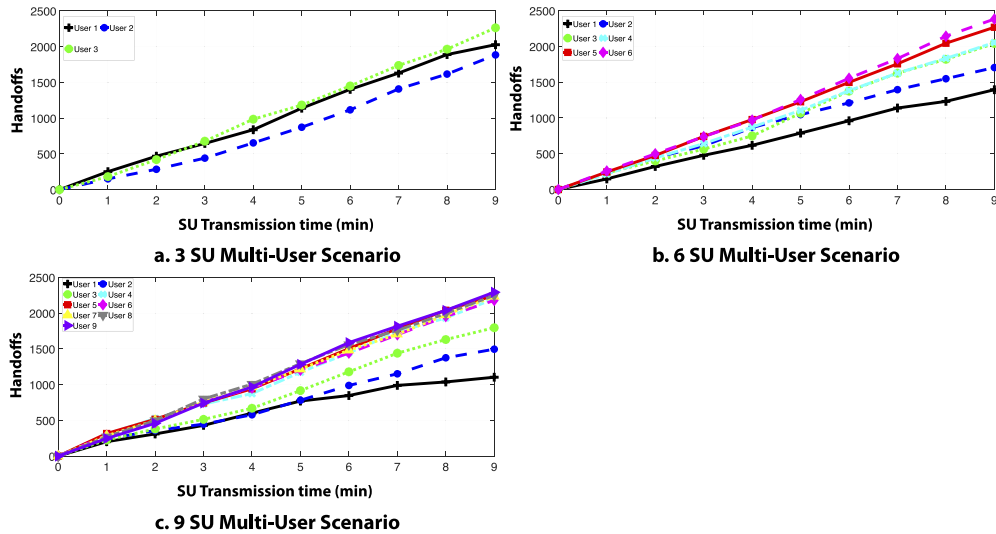


Figure 10. Handoffs number using TOPSIS with a 20 % collaboration level for: (a) 3 SU, (b) 6 SU and (c) 9 SU.

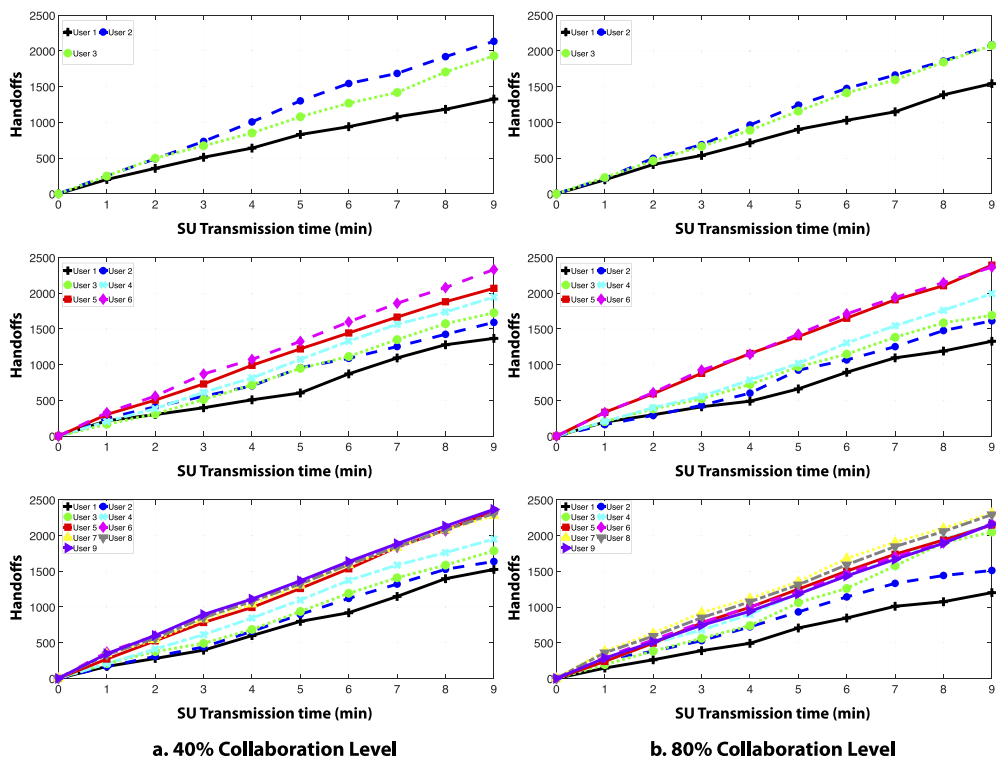


Figure 11. Handoffs number using TOPSIS with: (a) 40 % collaboration level for 3 SU, 6 SU and 9 SU, (b) 80 % collaboration level for 3 SU, 6 SU and 9 SU.

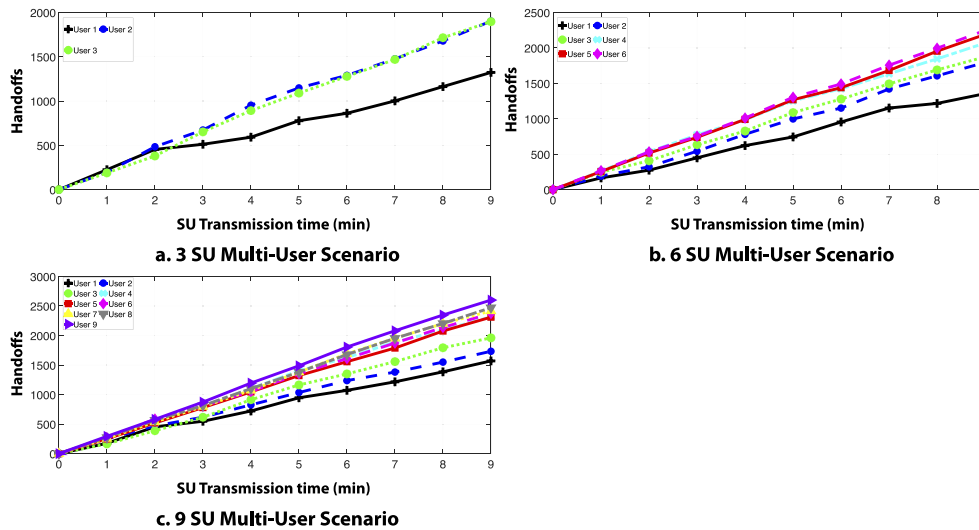


Figure 12. Handoffs number using VIKOR with 20 % collaboration level for: (a) 3 SU, (b) 6 SU and (c) 9 SU.

3.2. Total handoffs analysis

Figure 14 presents the comparative analysis for the 3 SU multi-user access scenario with all three levels of collaboration using the TOPSIS decision-making technique. Based on collaboration levels, it is identified that for 1 SU and 3 SU access, the highest number of handoffs with the lowest performance was for the 20 % collaboration level; the best performance was for the 40 % collaboration level. For 2 SU access, the behavior is inverse; the best performance was for the 20 % collaboration level and the lowest performance was for the 40 % collaboration level. The average difference between the 20 % and 40 % collaboration level is 428 handoffs, between the 20 % and 80 % collaboration level is 292 handoffs and between the 40 % and 80 % collaboration level is 136 handoffs.

Figure 15 presents the comparative analysis for the 6 SU multi-user access scenario with all three levels of collaboration using the TOPSIS decision-making technique. Based on collaboration levels, it was identified that the best performance is achieved for the highest collaboration levels except for 5 SU access where the 80 % collaboration level exceeds the 20 % collaboration level by 126 handoffs. On average, the difference between the 40 %–80 % collaboration level is 36 handoffs, a low ratio when compared to the 20 % collaboration level. The average difference between the 20 %–40 % collaboration level is 136 handoffs, between the 20 % and 80 % collaboration level is 119 handoffs and between the 40 % and 80 % collaboration level is 84 handoffs.

Figure 16 presents the comparative analysis for the 9 SU multi-user access scenario with all three levels of collaboration using the TOPSIS decision-making technique. Based on collaboration levels, similar behavior is identified between 20 % and 80 % collaboration levels. The 40 % collaboration level for accesses greater than 4 SU has similar behavior to 20 % and 80 % collaboration levels, for 3 SU and 4 SU it has the best performance with the fewest handoffs, and for 1 SU it has the lowest performance with the lowest number of handoffs. Although the 20 % collaboration level has the lowest performance, it is important to highlight the similarity of behaviors between levels of collaboration. The average difference between the 20 %–40 % collaboration level is 137 handoffs, between the 20 % and 80 % the collaboration level is 86 handoffs and between the 40 % and 80 % the collaboration level is 149 handoffs.

Figure 17 presents the comparative analysis for the 3 SU multi-user access scenario with all three levels of collaboration using the VIKOR decision-making technique. Depending on the levels of collaboration, linearity is identified for the 40 % and 80 % collaboration level; for the 80 % collaboration level you get the lowest number handoff with the best

performance for 2 SU and 3 SU access, for 1 SU access you get the highest number of handoffs with the minimum performance; for the 40 % collaboration level you get the highest number of handoffs with the minimum performance for 3 SU access, for 1 SU and 2 SU it is located at an intermediate point of performance. For the 20 % collaboration level, you get the lowest number of handoffs with the best performance for 1 SU access; for 2 SU access you get the highest number of handoffs with the minimum performance. The average difference between the 20 % and 40 % collaboration level is 136 handoffs, between the 20 % and 80 % collaboration level is 197 handoffs and between the 40 % and 80 % collaboration level is 202 handoffs.

Figure 18 presents the comparative analysis for the 6 SU multi-user access scenario with all three levels of collaboration using the VIKOR decision-making technique. For the 80 % collaboration level you get the highest number of handoffs with the minimum performance for all multi-user access. Similar behavior is identified between 20 % and 40 % collaboration levels. For these two levels, the biggest difference is obtained for 6 SU access where the 20 % collaboration level exceeds the 40 % by 146 handoffs. The average difference between the 20 %–40 % collaboration level is 74 handoffs, between the 20 % and 80 % collaboration level is 357 handoffs and between the 40 % and 80 % collaboration level is 383 handoffs.

Figure 19 presents the comparative analysis for the 9 SU multi-user access scenario with all three levels of collaboration using the VIKOR decision-making technique. Depending on the levels of collaboration, similar behavior is identified between the three levels of collaboration. The 40 % collaboration level presents the best metrics with the lowest handoffs levels for 3 SU up to 9 SU accesses. For the 80 % collaboration level, you get the best metrics for 1 SU and 3 SU accesses. The 20 % collaboration level is between 40 % and 80 % collaboration levels for accesses between 5 SU and 9 SU. The average difference between the 20 %–40 % collaboration level is 104 handoffs, between the 20 % and 80 % collaboration level is 96 handoffs and between the 40 % and 80 % collaboration level is 149 handoffs.

3.3. Analysis of multicriteria techniques

Tables 6, 7 and 8 present the metrics obtained according to the TOPSIS and VIKOR multi-criteria decision-making techniques for the 3 SU, 6 SU and 9 SU scenario.

For the 3 SU scenario, VIKOR generates the best metrics in 67 % of SU for 20 % and 80 % collaboration levels. For the 40 % collaboration level, TOPSIS generates the best metrics in 67 % of SU.

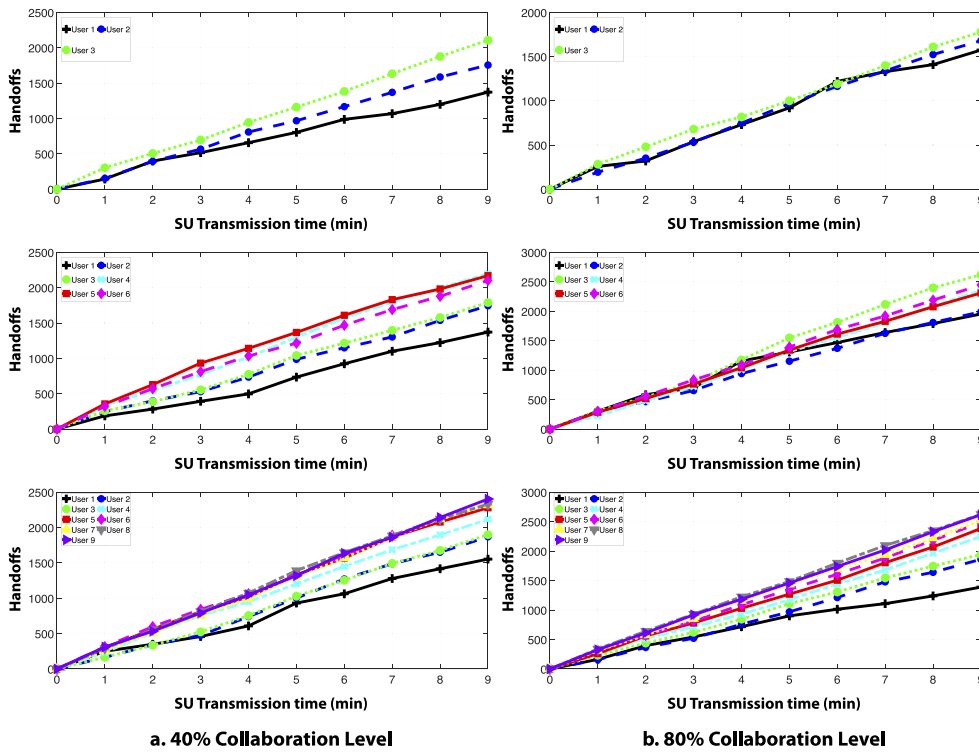


Figure 13. Handoffs number using VIKOR with: (a) 40 % collaboration level for 3 SU, 6 SU and 9 SU, (b) 80 % collaboration level for 3 SU, 6 SU and 9 SU.

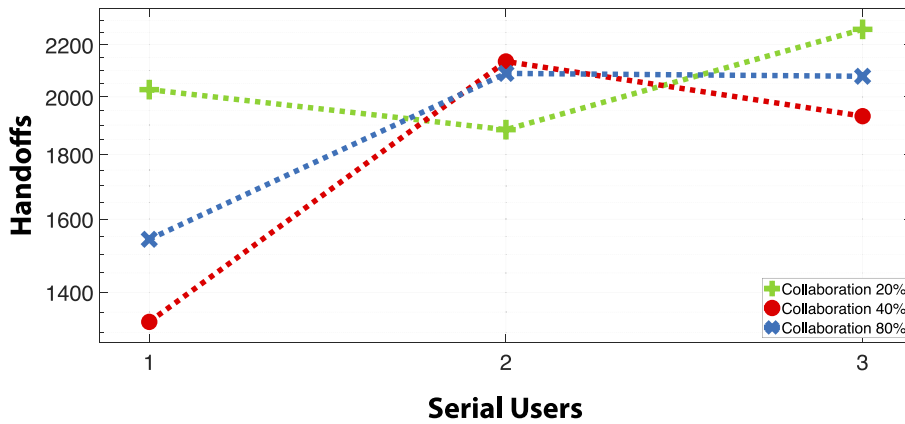


Figure 14. Total number of handoffs using TOPSIS with 20 %, 40 %, and 80 % collaboration levels for 3 SU multi-user access scenarios.

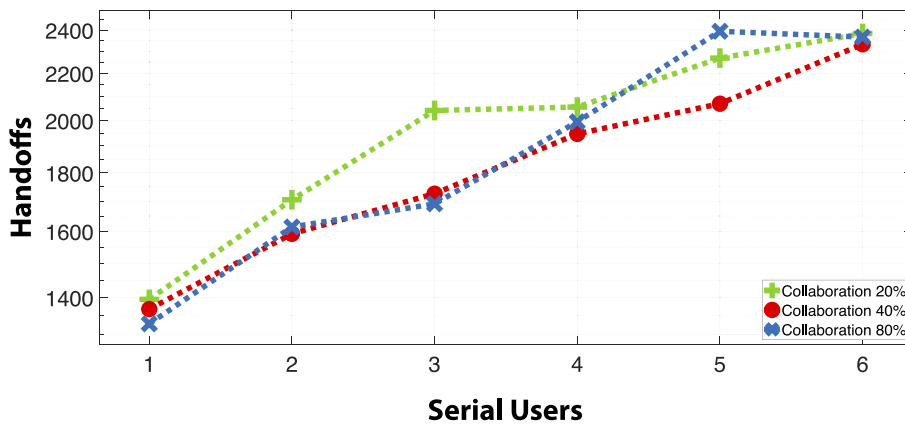


Figure 15. Total number of handoffs using TOPSIS with 20 %, 40 %, and 80 % collaboration levels for 6 SU multi-user access scenarios.

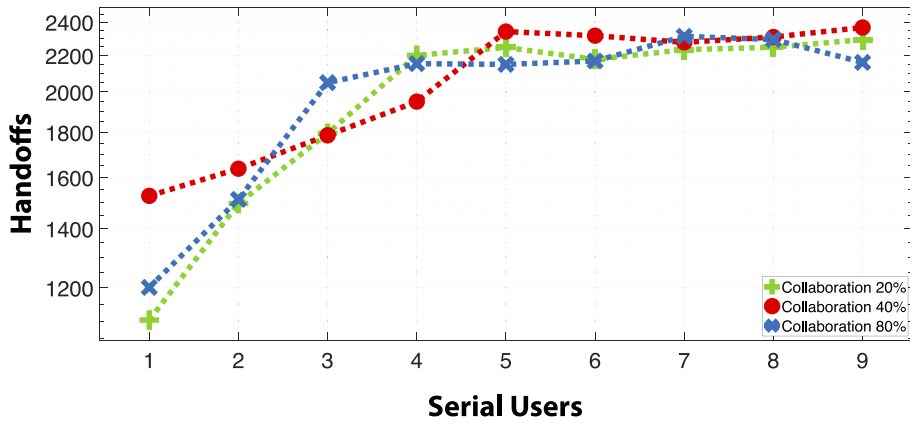


Figure 16. Total number of handoffs using TOPSIS with 20 %, 40 %, and 80 % collaboration levels for 9 SU multi-user access scenarios.

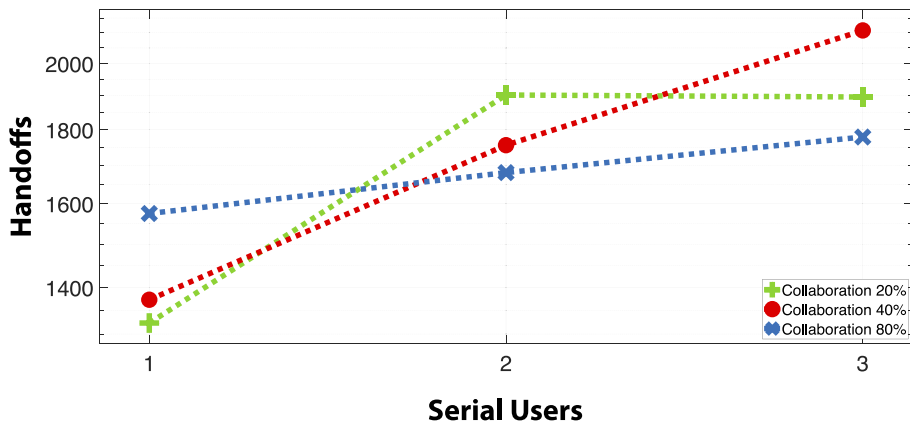


Figure 17. Total number of handoffs using VIKOR with 20 %, 40 %, and 80 % collaboration levels for 3 SU multi-user access scenarios.

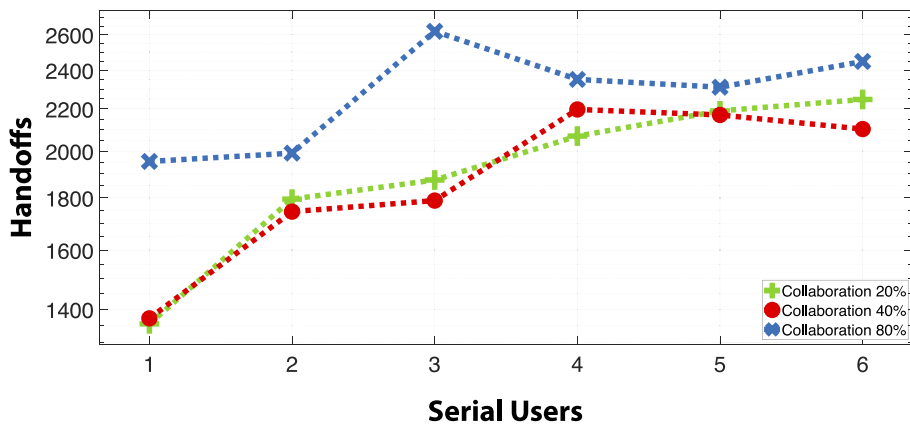


Figure 18. Total number of handoffs using VIKOR with 20 %, 40 %, and 80 % collaboration levels for 6 SU multi-user access scenarios.

For the 6 SU scenario, TOPSIS generate the best results for 40 % and 80 % collaboration levels, with the exception of access to 6 SU for the 40 % collaboration level and 5 SU for the 80 % collaboration level, where VIKOR outperforms TOPSIS by 230 handoffs and 84 handoffs respectively. For the 20 % collaboration level, VIKOR had the best results for 67 % of SU.

For the 9 SU scenario, the MCDM that generated the best results was TOPSIS, with the exception of access to 5 SU for the 40 % collaboration level and 3 SU for the 80 % collaboration level, where VIKOR outperforms TOPSIS by 61 handoffs and 105 handoffs respectively.

3.4. Discussion

For the two decision-making models in all three levels of collaboration with the different multi-user access scenarios, there was an increase in the number of handoffs as the number of users increased. For all the implemented stages, the 9 SU access generated the highest number of handoffs; and the 1 SU access generated the lowest number of handoffs.

According to the comparative analysis between the total number of handoffs obtained in minute nine and the three levels of collaboration using the TOPSIS decision-making technique, it was found that for

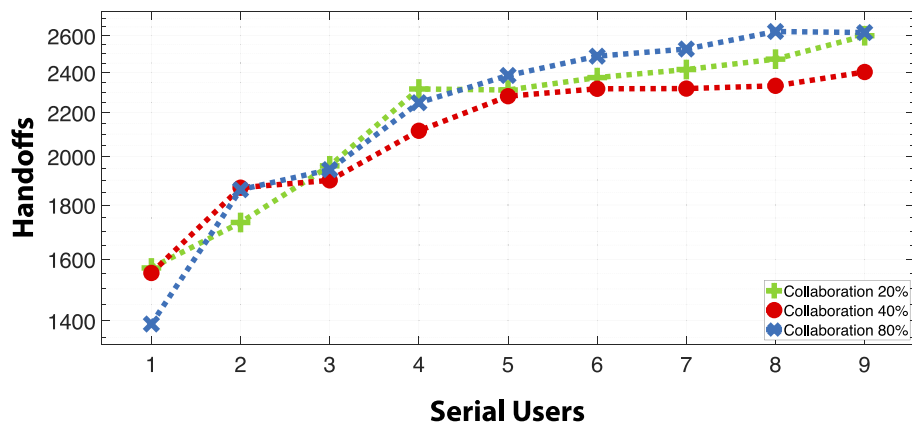


Figure 19. Total number of handoffs using VIKOR with 20 %, 40 %, and 80 % collaboration levels for 9 SU multi-user access scenarios.

Table 6. Total handoffs number for 3 SU multi-user access.

User Number	Collaboration Level					
	20		40		80	
	TOPSIS	VIKOR	TOPSIS	VIKOR	TOPSIS	VIKOR
1	2027	1323	1326	1373	1542	1575
2	1884	1902	2134	1756	2088	1681
3	2263	1896	1931	2108	2077	1779

Table 7. Total handoffs number for 6 SU multi-user access.

User Number	Collaboration Level					
	20		40		80	
	TOPSIS	VIKOR	TOPSIS	VIKOR	TOPSIS	VIKOR
1	1395	1355	1368	1372	1328	1954
2	1705	1795	1592	1745	1614	1991
3	2041	1874	1726	1789	1691	2620
4	2055	2069	1947	2197	1995	2351
5	2268	2190	2069	2170	2394	2310
6	2383	2247	2332	2102	2366	2448

Table 8. Total handoffs number for 9 SU multi-user access.

User Number	Collaboration Level					
	20		40		80	
	TOPSIS	VIKOR	TOPSIS	VIKOR	TOPSIS	VIKOR
1	1103	1570	1525	1553	1201	1390
2	1495	1733	1637	1869	1511	1861
3	1795	1960	1786	1899	2049	1944
4	2200	2316	1950	2115	2153	2248
5	2246	2311	2341	2280	2149	2385
6	2177	2374	2316	2317	2168	2487
7	2233	2416	2276	2318	2312	2526
8	2247	2471	2308	2332	2293	2624
9	2292	2600	2366	2403	2160	2618

scenarios with 3 SU multi-user access levels there is an average decrease in the number of handoffs equal to 12 % if the collaboration level increases from 20 % to 40 %. If the collaboration level increases from 20 % to 80 %, the average decrease in the number of handoffs is 7 %. And finally, if the collaboration level increases from 40 % to 80 %, there is no decrease in the number of handoffs; the number of handoffs increases by

an average of 7 %. For the VIKOR decision-making technique, if the collaboration level increases from 20 % to 40 % there is an average increase in the number of handoffs of 2 %. If the collaboration level increases from 20 % to 80 %, there is an average increase in the number of handoffs of 0.4 %. And finally, if the collaboration level increases from 40 % to 80%, the number of handoffs decreases by an average of 2 %.

According to the comparative analysis between the total number of handoffs obtained in minute nine and the three levels of collaboration using the TOPSIS decision-making technique, it was found that for scenarios with multi-user access levels of 6 SU, there is an average decrease in the number of handoffs equal to 7 % if the collaboration level increases from 20 % to 40 %. If the collaboration level increases from 20 % to 80 %, the average decrease in the number of handoffs is 4 %. And finally, if the collaboration level increases from 40 % to 80 %, there is no decrease; the number of handoffs increases by an average of 7%. For the VIKOR decision-making technique, if the collaboration level increases from 20 % to 40 %, there is an average decrease in the handoff number of 1 %. If the collaboration level increases from 20 % to 80 %, there is an average decrease in the number of handoffs of 20 %. And finally, if the collaboration level increases from 40 % to 80 %, the number of handoffs increases by an average of 22 %.

According to the comparative analysis between the total number of handoffs obtained in minute nine and the three levels of collaboration using the TOPSIS decision-making technique, it was found that for scenarios with multi-user access levels of 9 SU, there is an average increase in the number of handoffs from 16 % if the collaboration level increases from 20 % to 40 %. If the collaboration level increases from 20 % to 80 %, the average increase in the number of handoffs is 8 %. And finally, if the collaboration level increases from 40 % to 80 %, there is no increase; the number of handoffs decreases by an average of 2 %. For the VIKOR decision-making technique, if the collaboration level increases from 20 % to 40 %, there is an average decrease in the number of handoffs of 3 %. If the collaboration level increases from 20 % to 80 %, there is an average decrease in the number of handoffs by 1 %. And finally, if the collaboration level increases from 40 % to 80 %, the number of handoffs increases by an average of 4 %.

According to the analysis between multi-criteria decision-making techniques, the three levels of collaboration and multi-user access scenarios, TOPSIS was found to have the best results for 40 % and 80 % collaboration levels in scenarios of 3 SU, 6 SU and 9 SU. It is important to highlight a variation in this group. For the 80 % collaboration level in 3 SU, TOPSIS generates the best metric in 33 % of SU. For the 20 % collaboration level, VIKOR presents the best metrics. However, even if TOPSIS generates a higher number of handoffs, it maintains good performance with differences not exceeding 90 handoffs.

For the 9 SU scenario, the average difference between TOPSIS and VIKOR at the 20 %, 40 %, and 80 % collaboration levels is 218 handoffs, 78 handoffs, and 255 handoffs respectively. For the 6 SU scenario, the average difference between TOPSIS and VIKOR for 20 %, 40 %, and 80 % collaboration levels is 88 handoffs, 134 handoffs, and 409 handoffs, respectively. For the 3 SU scenario, the average difference between TOPSIS and VIKOR for 20 %, 40 %, and 80 % collaboration levels is 363 handoffs, 201 handoffs, and 246 handoffs, respectively.

4. Conclusions

CR is a broad field with multiple publications. Challenges grow exponentially depending on applications and it is impossible to list all areas of research that can arise within a CRN. The constant work is to propose strategies that allow integrating scalable adaptive strategies of low computational load and that are also able to solve problems of greater complexity. This work was to allow analyzing simultaneously and in the same radio environment the exchange of information between SU and how SU decisions affect the utility of the other SU. A decision-making proposal was developed through the implementation of four modules. The results were presented in three multi-user access scenarios and three levels of collaboration.

According to the metrics obtained, the performance showed a behavior inversely proportional to the number of multi-user accesses. This indicates that in order to analyze the accuracy of the SU decisions and the estimation models of the behaviors of the radio environment, it is essential to contemplate the access of multiple users. In the context of

collaborative strategies—depending on the number of SU accesses—it was found that for the lowest collaboration level (20 %) you get the biggest handoff increase, for the highest collaboration level (80 %) you get an intermediate handoff increase, and for the intermediate level (40 %) you get the lowest handoff increase. These results show that implementing collaboration strategies improves decision-making performance indicators. According to the results obtained in the decision-making process when implementing multi-user serial access, it was found that TOPSIS had the best results in most of the cases analyzed. For cases where VIKOR generated a smaller number of handoffs, TOPSIS maintained good performance with differences not exceeding 90 handoffs.

5. Future work

The advances are promising, many questions remain to be answered. Decision-making algorithms must take advantage of advances in software and hardware, strategies must be scalable to ease the computational load and be able to solve problems of greater complexity. The future work is proposed from two approaches.

According to the strategy proposed in this research, the first approach is to apply it in actual conditions, with real users. To apply and evaluate the proposed architecture, including the internal operations of each module, embedded systems that allow the implementation of software-defined cognitive engines are required. The Universal Software Radio Peripheral (USRP) is a good strategy; it provides a software-defined architecture that allows rapid prototyping and implementation of wireless systems with customized signal processing (Lipski et al., 2021; Zhao et al., 2021). USRP include a combination of FPGA-based processors. These devices can be used for applications such as multiple-input, multiple-output (MIMO), and LTE/WiFi testbeds (Darak et al., 2017; Kumar et al., 2013).

The second approach is decision-making analytics. The challenges grow exponentially; it is impossible to list all the challenges that arise within a CRN. Therefore, the ongoing work is to identify and propose efficient algorithms (new or hybrid) that allow using cognitive engines to integrate accessible adaptive learning algorithms with a low level of computational load.

Declarations

Author contribution statement

Diego Armando Giral-Ramírez, Cesar Augusto Hernández-Suarez & Luis Fernando Pedraza-Martínez: 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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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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