Analysis and assessment software for multi-user collaborative cognitive radio networks

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ABSTRACT

Computer simulations are without a doubt a useful methodology that allows to explore research queries and develop prototypes at lower costs and timeframes than those required in hardware processes. The simulation tools used in cognitive radio networks (CRN) are undergoing an active process. Currently, there is no stable simulator that enables to characterize every element of the cognitive cycle and the available tools are a framework for discrete-event software. This work presents the spectral mobility simulator in CRN called “App MultiColl-DCRN”, developed with MATLAB’s app designer. In contrast with other frameworks, the simulator uses real spectral occupancy data and simultaneously analyzes features regarding spectral mobility, decision-making, multi-user access, collaborative scenarios and decentralized architectures. Performance metrics include bandwidth, throughput level, number of failed handoffs, number of total handoffs, number of handoffs with interference, number of anticipated handoffs and number of perfect handoffs. The assessment of the simulator involves three scenarios: the first and second scenarios present a collaborative structure using the multi-criteria optimization and compromise solution (VIKOR) decision-making model and the naïve Bayes prediction technique respectively. The third scenario presents a multi-user structure and uses simple additive weighting (SAW) as a decision-making technique. The present development represents a contribution in the cognitive radio network field since there is currently no software with the same features.

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1. INTRODUCTION

Cognitive radio (CR) is a technology intended to overcome the problem of inefficient use of the spectrum. CR is characterized by perceiving, learning, planning (decision-making tasks) and acting according to the current conditions of the network. In contrast with traditional networks, CR has two types of users. The primary user (PU) that has licensed access to frequency bands and the unlicensed secondary user (SU) that opportunistically uses the spectrum [1], [2]. The objective of a cognitive radio network (CRN) consists on letting the SU have access to an available frequency channel within a licensed band, without interfering with the activity of the PU [1], [3]. This is achieved through a management model known as the cognitive cycle [4]. The process of a SU changing its operation frequency is called spectral mobility [5], [6] which gives way to a new type of handoff in CRN (spectral handoff) [7]. To characterize spectral mobility in CRN, the process of SU decision-making needs to be analyzed in terms of spectrum variation and the actions performed by other SU. The goal is to define strategies that allow SU to make decisions and exchange information collaboratively [8].

Furthermore, these features need to be assessed based on the network architecture, which can be classified as architecture with infrastructure and without infrastructure [9], [10]. In general, infrastructure-based architectures can be classified as decentralized and centralized and architectures without infrastructure are categorized into distributed networks [9]. In the field of CRN, the developed models are aimed at solving centralized architecture problems [10]–[16]. Therefore, decision-making models must be identified for CRN that can operate with decentralized architectures.

Simulation is a useful methodology for network data analysis since it can ponder research queries and explore low-cost time-efficient prototypes compared to real implementations and experiments. Simulators can offer virtual environments with a variety of desirable features that enable the modeling of networks in terms of specific criteria and analyze performance in different scenarios [17]–[19]. Based on realistic scenarios for analysis and assessment of the spectral mobility process, it is necessary to include computing applications that can model said scenarios. There are currently no open access or commercial tools available that can handle these features (spectral mobility in CRN, multi-user access, collaborative scenarios, decision-making activities, decentralized architectures). Regarding previous research projects, it is noteworthy to mention that no articles were found discussing CR simulation tools that can simultaneously integrate spectral mobility, multi-user access, collaborative scenarios, decision-making and decentralized architectures. The research reviewed in this document focuses on relevant research linked to the development of CRN-oriented simulators.

A series of simulation platforms based on discrete events have been used in communication network research which include CR modules. NS-2, NS-3, GloMoSiM, NetSim and OMNeT++, have multiple advantages. In literature, different articles have focused on stating comparative analyses to identify application areas. Khana *et al.* [20] compare the open-source simulators using memory usage and processing criteria as well as computing times and scalability through the simulation of a MANET routing protocol. The comparative analysis includes NS-2, NS-3, OMNeT++ and GloMoSiM given that they are well-known in the academia [21]. The analysis involves the CR modules available in NS-3 and OMNeT++ and the parameters include medium access control (MAC) protocols, maximum PU supported, maximum SU supported, multi-channel access, network capacity, type of interface and documentation.

The different CR modules available are open source and their frameworks are developed for platforms such as NS-3 and OMNET++. Ferreira *et al.* [22] propose a cognitive cycle in the NS-3 simulator, which includes collaborative detection and a CR resource programmer. The proposal includes a PU behavior characterization model and a methodology to measure the impact of detection mechanisms for different LTE and 5G networks. The work in [23] discusses a discrete simulation model for CRN in OMNeT++ called CR simulator. The proposed framework has all the benefits of modular object-oriented concepts derived from OMNeT++ and can be easily extended to any network architecture and nodes based on discrete components. Furthermore, the simulator offers components for some basic CR features such as spectrum detection and reconfigurable links.

As seen in the previous framework, CR simulation tools are being constantly validated. Currently, there is no stable simulator that can characterize each element of the cognitive cycle. The viability of having a single tool that can meet all the requirements of the academic and research community is very unlikely. Due to the exponential growth of applications and multiple areas of study in CRN, independent simulators can be seen for solving specific CRN problems. The work in [24] discusses the event-based open source Komondor software and the tool simulates the physical layer of next-generation wireless local area networks (WLAN). It uses a preliminary architecture based on machine learning, which allows to handle self-configuration scenarios in different communication levels. The simulator is based on Comp C++ libraries without a graphical interface. In study [25], the app collaborative CRN is developed to assess the performance of different collaborative algorithms in the spectral decision-making process for CRN based on real occupancy data. The simulator is based on MATLAB's programming language and includes a graphical interface.

The contribution and goal of this work is to develop a simulation tool that can analyze the spectral mobility process in decentralized architectures. The tool is designed under a seven-module architecture and includes a collaborative analysis, multi-user parameterization and six decision-making modules (one non-predictive model and five predictive models). The simulation tool known as "App MultiColl-DCRN" was developed in MATLAB R2020a and designed to allow the user to operate under a friendly environment that can set parameters based on the desired tests. In addition to the previously described features, it uses real spectral occupancy data measured in the global system for mobile communications (GSM) and Wi-Fi bands. These measures are incorporated in order to showcase real PU behavior.

According to the contribution, objectives and analysis of the previously described state of the art, three differences were identified with respect to the published research. The first difference is that no work was identified that would allow each of the modules developed in the "App MultiColl-DCRN" to be included in the same scenario. The second difference is the implementation of the real behavior of the licensed users within the simulation environment. The third difference is the performance metrics, the results obtained in each of the analyzed works, present exclusive metrics that analyze the effectiveness of the proposed models, characteristics of spectral mobility and quality of service are not studied.

The simulator has eight assessment variables (metrics): average accumulative handoff, average accumulative failed handoff, average bandwidth, average accumulative delay, average accumulative throughput, average accumulative handoff with interference, average accumulative perfect handoff and average accumulative anticipated handoff. Each assessment metric is obtained during the transmission timeframe of the SU, which can be adjusted by the user during the parameter definition stage. This work is organized into three sections. Section 2 describes the methodology including each module of the simulator, the module logic as well as the inputs, outputs and functions. Section 3 presents the results obtained for specific cases. The final section establishes conclusions on the overall work.

2. RESEARCH METHOD

The application multi-user collaborative spectral decision for decentralized cognitive radio networks or "App MultiColl-DCRN" was developed in the app designer tool from MATLAB 2020a. It has 106 functions and three graphical interfaces and the simulator operates based on power metrics from two types of networks: GSM and Wi-Fi. Nonetheless, other metrics can be considered.

Figure 1 presents a block diagram of the simulator. The architecture is module-based and each output variable and internal variable is represented by a color. Figure 1 presents the color convention used for the module description. Table 1 gives a general overview of the modules.

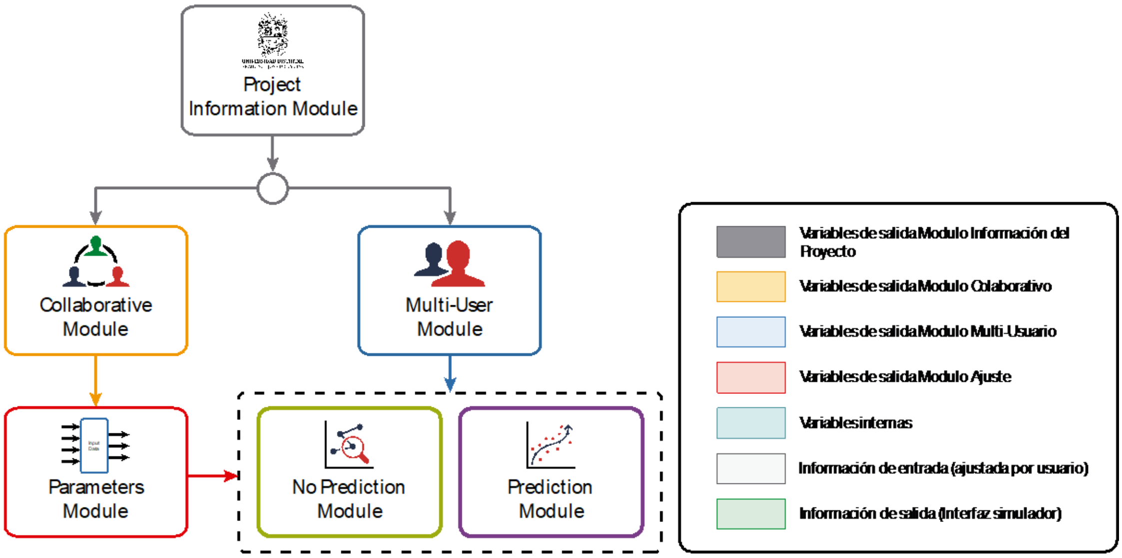

Figure 1. Module-based architecture and color code in the APP MultiColl-DCRN

Table 1. Module description of APP MultiColl-DCRN

Module	Description
Project Information	The basic information of the project and network type is parameterized
Collaborative	The collaborative scenarios are parameterized, by adjusting the quantity and method of information selection.
Multi-User	The number of serial users, random users and multichannel features is parameterized.
Parameters	The threshold, noise floor, bandwidth fixed, and multichannel variables are parameterized. The traffic level and transmission time are characterized.
No Prediction	The non-prediction model is set
Prediction	The prediction algorithms Markov Chain, Genetic Algorithm, Naive Bayes, Logistic Regression and Time Series are parameterized.
Output	The case study is executed (Run), the window can be closed (Close) and the new interface can be updated (Update).

The simulator is designed to guide the user throughout the parameterization process and the parameters are initially disabled by default. The purpose of this feature is to reduce the probability of wrongful adjustments. Hence, the modules will be enabled in an orderly manner if the adjustments are properly made. Figure 2 shows the main environment of the simulation tool. The subsequent sections describe in detail each module including input variables, output variables and the methodology involved.

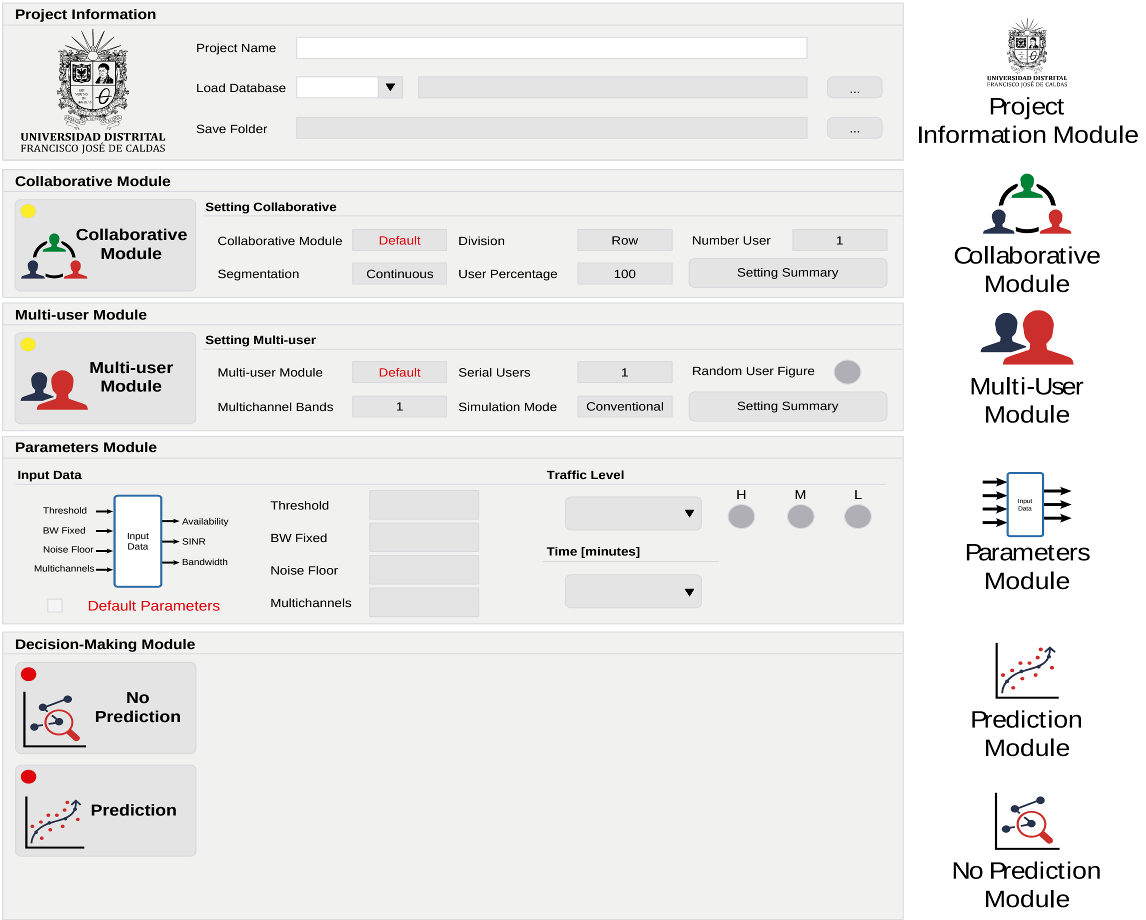

Figure 2. Graphical interface of the MultiColl-DCRN App

2.1. Project information module

The first module to parameterize is "Project Information". This module contains all the elements linked to the folder name and path where the results of the corresponding simulations will be stored. Furthermore, the selection of the spectral occupancy database is carried out. The simulator creates by default a folder with the name "App MultiColl-DCRN" in the path defined in "*Save folder*". This folder includes all the projects (subfolders) created based on the generated "Project name". The description of each input and output variable is shown in Tables 2 and 3 with their respective adjustment.

Table 2. Input variables "Project Information"

Variable	Description
Project Name	The results of each simulation are stored in a specific path and folder. The path is established in the "*Save Folder*" variable and the folder is created automatically with the name "App MultiColl-DCRN". The user can store the results of multiple simulations in this folder and subfolders can be created to differentiate the results. These names correspond to the allocation made by the user in the "*Project Name*" variable
Load Database	The database linked to the network type is chosen: GSM and Wi-Fi. The simulator has the possibility to load a database different from the predefined ones. This feature is enabled by choosing the "Custom" option
Save Folder	The path where the results of each simulation are stored

Table 3. Output variables "Project Information"

Variable	Description
Project Name	Variable that visualizes the name assigned to the project
Database	Variable that visualizes the chosen technology
Power Training	Variable of the output module that corresponds to the power training matrix for the chosen network type
Power Evaluation	Variable of the output module that corresponds to the power training matrix for the chosen network type

2.1.1. Database

The simulator operates with two spectral occupancy databases: a power training database and a power evaluation database. The databases are comprised by the power measured experimentally in the GSM and Wi-Fi bands, in a previous metering campaign. This information delivers more reliable results since it uses real data of PU behavior. The training database is used to set the initial parameters of the spectral handoff algorithms and the assessment database is used to compute the metrics of the chosen algorithms. Both databases contain information on 500 frequency channels and 12,600 rows, for 1 hour in the case of power training and 9 minutes in the case of power evaluation, with 1/3 second resolution for both. The rows represent the time in seconds and the columns represent the frequency channels. The sampling time was 290 ms. Furthermore, the power training and power evaluation databases is classified based on the availability odds which allows to characterize the information according to traffic level: high traffic, medium traffic and low traffic. Based on this classification, the size of the database can be modified. The simulator has 12 databases in total: 6 for GSM and 6 for Wi-Fi.

2.2. Collaborative module

The structure adapted the collaborative strategy through a module of information exchange between SU. The methodology of the module consists of splitting the power matrix (database) into sub-matrices and establishing the shared information percentage through collaboration levels. Each sub-matrix represents a user, so the total of sub-matrices corresponds to the total number of users. The collaboration levels are chosen according to the data limits: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100%. These indicate how much data is involved in the collaboration process.

The collaborative module of the block diagram is presented in Figure 3, the blocks where the input and output signals converge correspond to the methodology that segments the power matrix based on collaboration levels. The module has three input parameters: two correspond to the variables adjusted by the user in the interface (collaboration level, number of users) and the third parameter is the adjusted database in the "Project Information" module. The amount of information to be shared is characterized based on the collaboration level, which requires the segmentation type, the division method and the percentage of collaboration levels. The description of each input and output variable are respectively presented in Tables 4 and 5 with their adjustment.

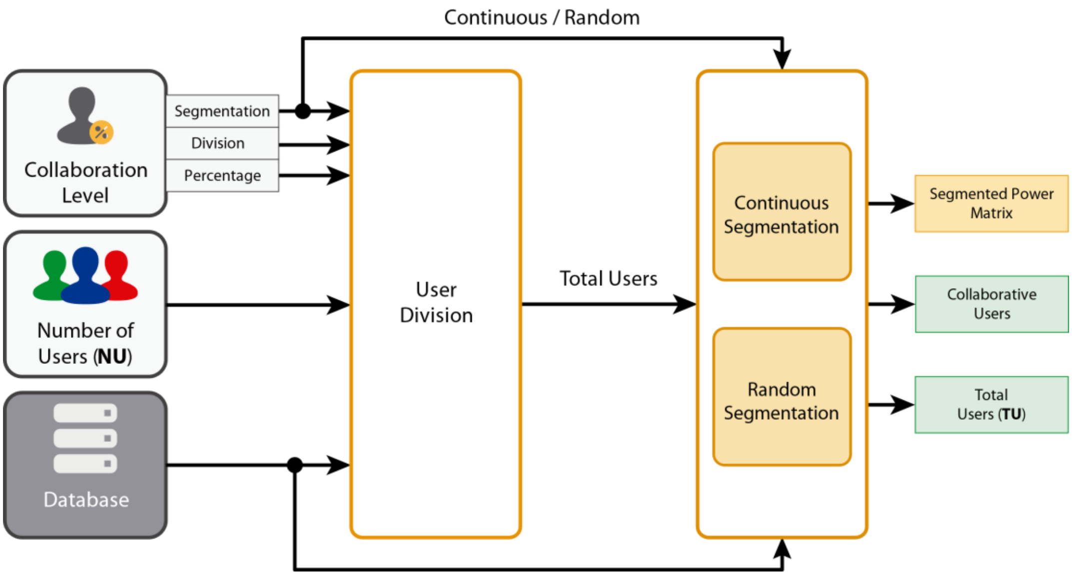

Figure 3. Block diagram of the collaborative module

Table 4. Input variables "Collaborative module"

Variable	Adjustment		Description
Collaboration level	Segmentation	Random	Random user selection for simulation
		Continuous	User selection in an ordered manner in terms of rows and columns
	Division	Row	*If *Number of Users*≥*10* then *Total Users=10×m:* Rows: are divided into 10 equal parts; Columns: are divided into *m* parts until the *NS* is completed; *If *Number of Users<10* then *Total Users=2×m*: Rows: are divided into two equal parts; Columns: are divided into *m* parts until the *NS* is completed
		Column	*If *Number of Users*≥*10* then *Total Users=10×k:* Columns: are divided into 10 equal parts; Rows: are divided into *k* parts until the NS is completed; *If *Number of Users<10* then *Total Users=2×k*: Columns: are divided into two equal parts; Rows: are divided into *k* parts until the NS is completed
	Percentage	10 %-100 %	Percentage of users included in the training
Number of users	1-1000 Users		Number of users (sub-matrices) that segment the power matrix
Databases	Type of network		Traffic matrix (GSM, Wi-Fi or Custom)

Table 5. Output variables "Collaborative module"

Variable	Description
Collaborative Users	Variable that shows the percentage of users that share information in the training phase
Total Users	Variable that shows the number of users that comprise the power matrix
Segmentation Power Training	Output variable of the collaborative module which contains the information of users chosen for the training process

2.3. Multi-user module

According to the need of including the effect of user decision-making on the utility of others, the implemented module can include multiple serial users, different types of applications, levels of priority and channel bands of different sizes. Furthermore, other features linked to the real behavior of the spectral band are included in the simulation at different time instants but with the same requirements. Figure 4 shows the block diagram of the multi-user module.

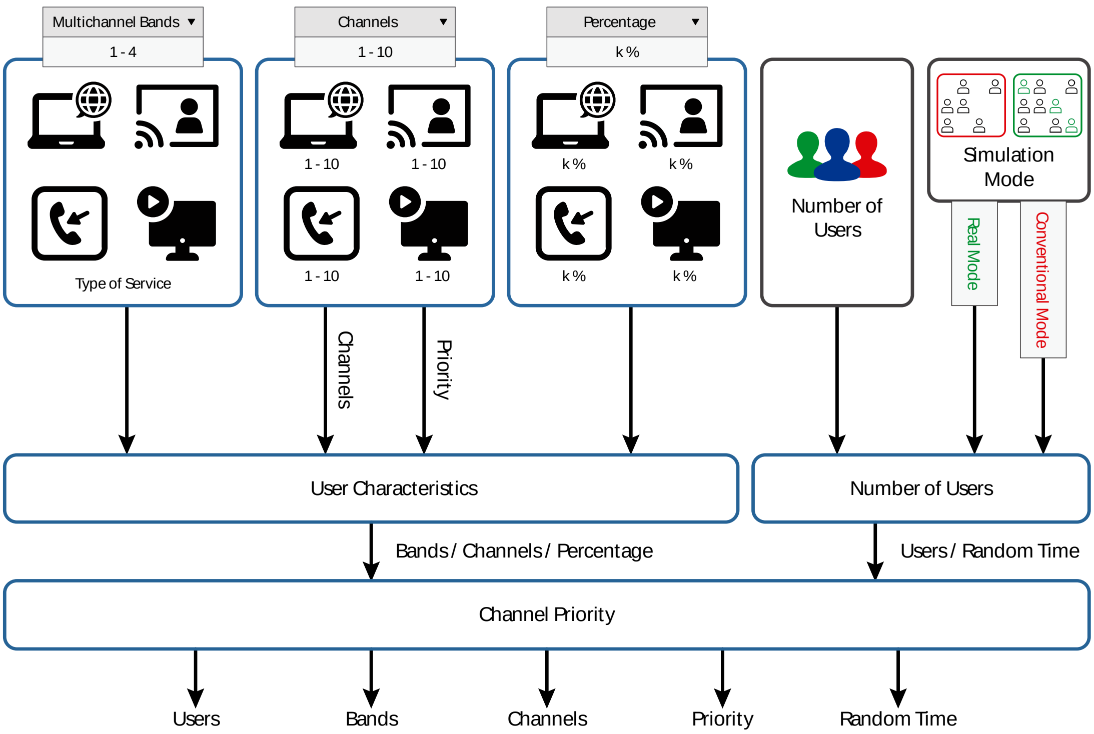

Figure 4. Block diagram of the multi-user module

The methodology of the module analyzes the behavior of the spectral decision-making model when multi-user access takes place. This is achieved through the generation of multiple users with different requirements. The module enables four types of services with the possibility of demanding priority and access to multiple channels, multiple users and their corresponding features which are included in the model throughout the entire simulation time. This methodology is called a conventional model. Furthermore, the module can include random users with no specific analysis goal. These users appear at random times and will not be present during the entire simulation but will have similar features to those that participated in the process. This structure is known as a real model. The description of each input and output variable with the corresponding adjustment is presented in Tables 6 and 7.

Table 6. Input variables "Multi-user module"

Variable	Adjustment	Description
Multichannel bands	1-4	Number of applications
Channels	1-10	Number of channels for the chosen application
Percentage	25%-50%-75%-100%	Percentage of users according to the application and the number of channels
Number of users	1-30	Number of serial users
Simulation mode	Real mode	Random users are included
	Conventional model	Random users are not included

Table 1. Output variables "Multi-user module"

Variable	Description
Users	Number of total serial users, depending on the simulation mode. For the real mode, the total users are equivalent to the sum between the adjusted users and the random users.
Bands	It contains the information on the number of selected applications
Channels	Output variable of the multi-user module, that contains the number of real users
Priority	Variable that allocates priority to the multichannel bands
Random Time	In real mode, variable that establishes the time in which random users enter and leave the simulation

2.4. Parameter module

This module enables to parameterize the levels of threshold, noise floor, bandwidth fixed and multi-channels. Furthermore, the traffic level and transmission time can also be characterized. The module has five inputs, three of them correspond to variables set by the user in the interface and the remaining two are the output matrices project information and collaborative module. The simulator assumes default values if the case study does not need to include collaborative analysis.

The goal of the module is to create a new database of input variables and information selection. To build the new database the information of threshold, noise floor, bandwidth fixed, multi-channels and time is stored. Afterwards, this new database is included in the prediction and non-prediction strategies. To build the information selection database, the module takes the training information from the power segmentation training matrix (generated through the collaborative module or by default) based on traffic levels. The same process is applied for the power evaluation matrix generated from project information. The output of the module is the database of parameterized variables and the power database for training and validation based on traffic levels. The description of each input and output variable and their respective adjustments are presented in Tables 8 and 9.

Table 8. Input variables "Parameters user"

Traffic Level	Element	Description
Traffic Level	High Medium Low	Traces of information that represent the behavior of the spectrum when the network has high, medium and low traffic levels
Time [minutes]	1-9	SU transmission time in minutes
Power Segmentation Training	Output variable of the parameter module containing the segmented power matrix based on traffic level focused on decision-making training	
Power Evaluation	Output variable of the parameter module containing the power matrix based on traffic level for the validation of decision-making techniques	
Threshold	Decision threshold to determine whether a spectral opportunity is available	
Noise floor	Average noise floor	
BW fixed	Fixed bandwidth for each frequency channel	
Multi-channels	Maximum number of available adjacent channels that can be grouped to form a single channel	

Table 2. Output variables “Parameters module”

Variable	Description
Threshold, Noise floor, BW fixed and multi-channels	Output variable linked to decision threshold, noise floor, fixed bandwidth and maximum number of channels available
Traffic level and Time [minutes]	Output variable linked to the traffic level and the SU transmission time in minutes
Power Segmentation Training Traffic and Power Evaluation Traffic	Output variable linked to the parameter module, corresponding to the segmented training matrix for selected traffic and the power assessment matrix for selected traffic

2.5. Decision-making module

This module contains different strategies that can be used to analyze the decision-making process (no prediction module: spectral decision, prediction module: Markov Chain, genetic algorithm, naive Bayes, logistic regression and time series) users can have access to six models (10 when adding 5 self-regressive models that comprise the time series), five models that serve as prediction techniques and a model for non-predictive analysis. Although each model is independent, five algorithms are required: initial parameter algorithm, multi-criteria ranking algorithm, multi-user algorithm, indicator prediction algorithm and performance metric algorithm. Hence, a brief description of the algorithms is carried out and the structure.

2.5.1. Initial parameter algorithm

Regardless of the adjustments on network type, traffic level, collaboration levels, number of users and analysis technique, the simulator requires to establish three initial parameters: availability, signal to noise plus interference ratio and bandwidth. These parameters are determined through the initial parameters function. In order to establish the initial parameters of the corresponding simulations, the software includes four input variables that must be parameterized by the user and each parameter is described in Table 8. Availability: the power data is transformed from a range between -147 and -40 into binary values according to the constraint given by the Threshold value where 1 represents the available frequency and 0 represents a non-available frequency. The obtained result is the availability matrix. SINR: the signal to noise plus interference ratio is determined based on the noise floor and the segmented power matrix. The subtraction between the input power data matrix and the noise floor variable defined by the user. Bandwidth: to determine the bandwidth the previously obtained availability matrix is used as well as the BW fixed and multi-channels. The bandwidth value is parameterized by the user in the software window.

2.5.2. Multi-criteria ranking algorithm

The ranking algorithm uses multi-criteria analysis to allocate a score for different channels. In order to set ranking, two functions are needed. The first one is called “Parameter ranking” which determines the availability probability criteria, the average availability time, the average SINR and the average bandwidth. The second function called ranking determines the channels with higher probabilities in terms of spectral opportunity. It uses the mentioned parameters and multiplies them by the vector of weights allocated.

The allocation of weights for the construction of the weights vector is based on the multi-criterion technique to be used. The techniques correspond to different handoff models algorithms and each one is programmed based on the state of the art. In total, there are 9 techniques in multi-criteria decision-making: analytic hierarchy process (AHP), fuzzy analytic hierarchy process (FAHP), feedback FAHP (FFAHP), simple additive weighting (SAW), managing epilepsy well (MEW), technique for order preference by similarity to ideal solution (TOPSIS), multi-criteria optimization and compromise solution (VIKOR), grey relational analysis (GRA) and random. Each handoff model requires the allocation of a 1×4 row vector of weights that can be adjusted by the user.

2.5.3. Multi-user search algorithm

This technique is in charge of spectral mobility. The algorithm uses the position vector delivered by the ranking algorithm to jump between columns in the availability matrix until an available channel can be found. When it is found, the row is changed in the matrix. Each row represents a time instant and the stop condition of the search algorithm. The stop condition is adjusted in the time parameter of the interface and corresponds to the output variable simulation time of the module parameters. Hence, the search algorithm carries row-wise jumps until the established time is concluded. The column-based and row-based jumps, the time and availability are stored in a database at the end of the simulation. The algorithm incorporates the analysis of spectral jumps for different serial users during the search characterization. The process is equivalent for a user with one channel, for multiple users with multiple channels, the most relevant difference is presented in the change of row given this is only carried out when all users find spectral opportunities or when the channel requirements exceed availability.

2.5.4. Precision indicator algorithm

Compares the channel prediction accuracy throughout the transmission time and assesses whether the availability predictions can lead to a beneficial use of the channels. The models used for channel predictions generate a new matrix based on availability where the channel states are defined by 1 (available) and 0 (busy). These probabilities are allocated to a matrix called prediction availability. The prediction of availability is carried out per channel during a given simulation time. The multi-user search algorithm is part of the prediction indicator algorithm yet the difference lies in one additional input and one additional output. The input corresponds to the prediction availability matrix obtained from the availability predictions which is compared to the evaluation availability matrix to obtain precision metrics. The results correspond to the output variable prediction.

2.5.5. Performance metric algorithm

The assessment of spectral handoffs is carried out through a training and validation matrix. For the analysis of results, the simulator exports the information through a database and a set of figures. The simulator generates five figures in two different formats: *.png and *.fig (MATLAB editable file). Both figures (*.png, *.fig) and the exported files (*.mat) are stored in the path chosen by the user (directory of the project information). The results correspond to the bandwidth figures (It is the number of total handoffs carried out), number of accumulative average handoff (it is the number of total handoffs carried out), number of accumulative average failed handoffs (it is the number of handoffs that the SU could not materialize since the spectral opportunities were unavailable), accumulative average delay (It is the total average time experienced by the SU) and accumulative average throughput (It is the effective data rate transmitted by the SU).

2.5.6. Prediction metrics

The models used to predict channels have additional metrics linked to the quality of the predictions made. These metrics are “Figure Anticipated”, “Figure Interference”, “Figure Perfect”. The results correspond to the figures of handoff with interference (It is the total number of reactive handoffs carried out once the PU arrives), perfect handoffs (It is the number of handoffs without interference carried out almost before the PU arrives without causing interference to the latter) and anticipated handoffs (It is the number of handoffs without interference carried out in an anticipated manner before the arrival of the PU).

2.6. No prediction module

The analysis of spectral mobility is carried out by implemented the algorithms in cascade: “Initial Parameter”, “Ranking”, “Search Algorithm” and “Figure and Data. For the assessment of the prediction module, metrics associated with the Quality of Service (QoS) are used. Five figures can be generated: bandwidth, failed handoffs, total handoffs, delay and throughput, each figure represents a performance metrics.

2.7. Prediction module

For the analysis of spectral mobility using prediction strategies, in addition to the ranking, search algorithm and figure and data blocks, the set of blocks linked to the model are also implemented. For the model assessment, the performance metric algorithm is used to deliver bandwidth, handoffs, failed handoffs, delay, and throughput values. Due to its programming structure, this module includes the prediction metrics block. However, the five predictive models do not generate prediction metrics.

2.7.1. Predictive models without prediction metrics

Markov Chain*:* this stochastic technique is based on the analysis of the inner dynamics of the system, the current state is predicted in simulation in a given time based on previous states. The goal is to deliver a transition probability matrix. The training transition matrix establishes the probabilities of the current and future states which are necessary for the implementation of chains, the probability of the training matrix is used in the validation matrix to quantify the spectral handoffs.

Genetic algorithm: metaheuristic optimization model inspired in the biological evolution. It allows generating a set of solutions through random actions similar to genetic mutations and recombinations. The model generates a training matrix, initially it establishes a random population, later, through selection, crossing and mutation, it produces a resulting population, equivalent to the training matrix. As an input parameter, the number of iterations (populations to be generated) is required. Feature that is selected using trial and error criteria.

2.7.2. Predictive models with prediction metrics

Naïve Bayes: it is a probabilistic model that depends on the interaction of different nodes that generate insights on each node involved in the process, through the Bayes approach. The proposed model uses the spectral occupancy training matrix as an input variable. The spectral information passes through the spectral information processing block before the training matrix is used. The block turns data into dichotomous series where 0 represents a 'busy' channel and 1 represents an available one. This information processing is the basis of the naïve Bayes algorithm.

Logistic regression: the main advantage of this method is that different explanative variables can be used simultaneously. This feature enables to determine the impact of explanative variables over the response variable. The proposed model uses the spectral occupancy matrix as an input. Before using it in the predictor training phase, the spectral information passes through the spectral information processing which turns data into dichotomous series where 0 represents a 'busy' channel and 1 represents an available one. This information processing is the basis of the logistic regression algorithm.

Time series: the goal of this purely proactive transfer model is to deliver predictions that define the behavior of PU and offer tools so that the system can react before the interference event. The stochastic models generate new data based on historical records through the adjustment of values for different variance delays based on a correlation coefficient. The time series models involved are auto-regressive (AR), mobile average (MA), auto-regressive mobile average (ARMA), auto-regressive integrated mobile average (ARIMA) and stationary auto-regressive integrated mobile average (SARIMA).

3. RESULTS AND DISCUSSION

The design, validation and implementation of "App MultiColl-DCRN", was carried out in Microsoft Windows 10 64-bit version, with respect to hardware, using an Intel® Core™ i7 - 2.80 GHz computer with 24 GB of RAM. The results obtained are presented in a set of figures obtained from parameterizing the collaborative and multi-user module using non-predictive and predictive models.

3.1. Results

Figures 5 and 6 show the metrics of bandwidth, throughput, failed handoffs and handoffs using the VIKOR non-predictive model. The transmission time is 9 minutes and the collaborative module was implemented by adjusting the collaboration levels to 10%, 40%, 70% and 100%. The GSM network was set with low traffic levels.

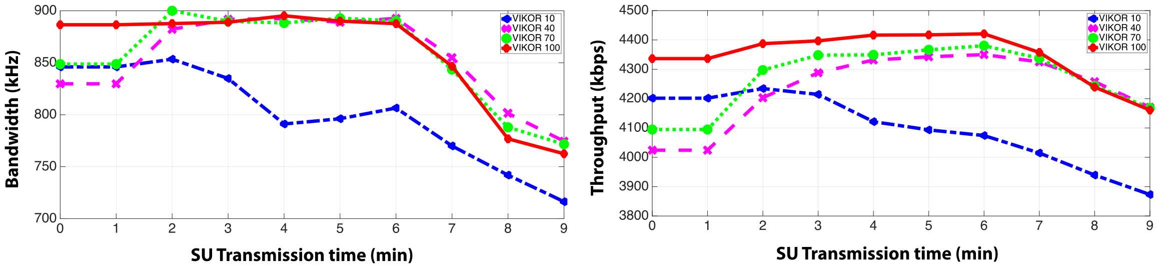

Figure 5. Bandwidth and throughput for the non-predictive VIKOR model with collaborative structure

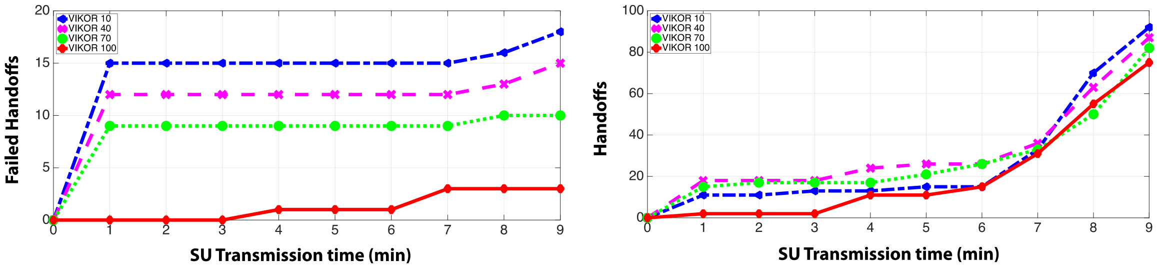

Figure 6. Failed handoffs and total handoffs for the non-predictive VIKOR model with collaborative structure

Figure 7 show the metrics of handoffs with interference, anticipated handoffs and perfect handoffs using naive Bayes predictive model. The transmission time is 9 minutes and the collaborative module was implemented by adjusting the collaboration levels to 10%, 40%, 70% and 100%. The GSM network was set with low traffic levels. Figures 8 and 9 show the metrics of bandwidth, throughput, failed handoffs and total handoffs using the SAW non-predictive model. The transmission time is 9 minutes and the multi-user module was implemented in conventional mode for 4 different scenarios (1 SU, 2 SU, 4 SU and 6 SU). The GSM network was chosen with low traffic levels.

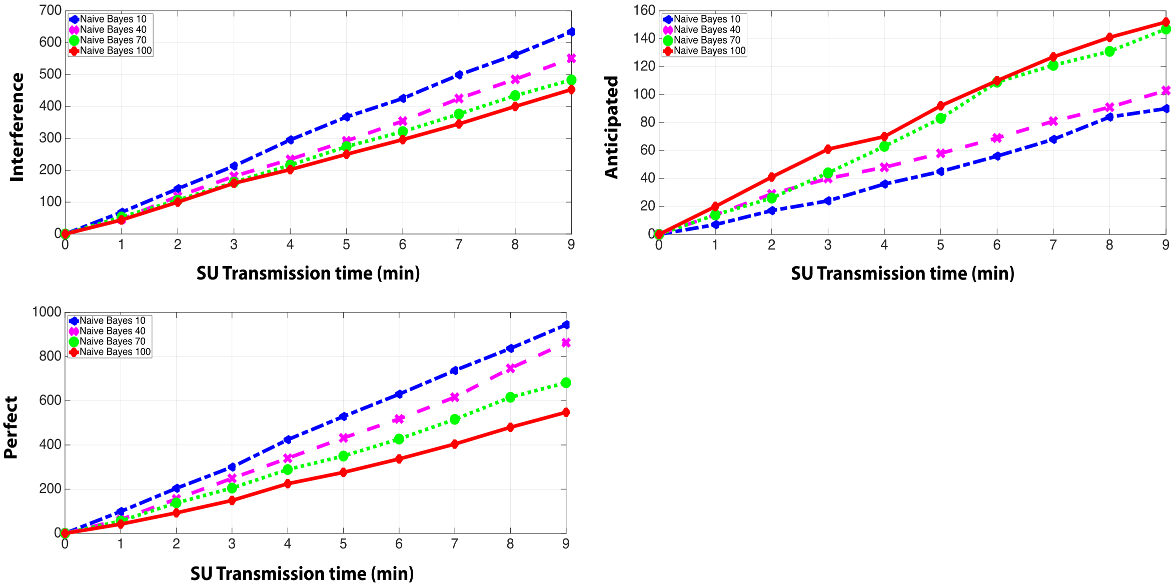

Figure 7. Handoffs with interference, anticipated handoffs and perfect handoffs for the prediction model naive Bayes with collaborative structure

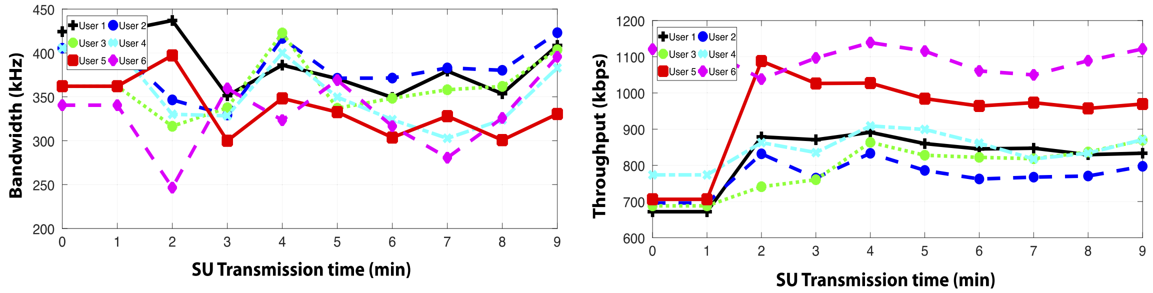

Figure 8. Bandwidth and throughput for the non-predictive SAW model with multi-user structure in conventional mode

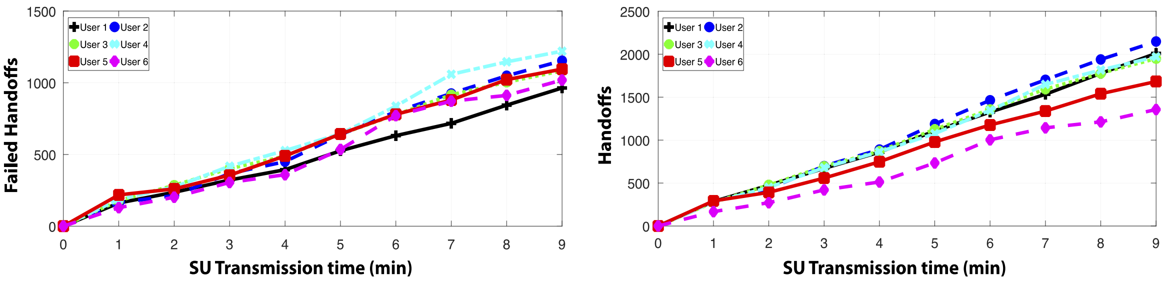

Figure 9. Failed handoffs and total handoffs for the non-predictive SAW model with multi-user structure in conventional mode

Figures 10 and 11 show the metrics of bandwidth, throughput, failed handoffs and total handoffs using the SAW non-predictive model. The transmission time is 9 minutes and the multi-user module was implemented in real mode for 4 different scenarios (1 SU, 2 SU, 4 SU and 6 SU). The GSM network was chosen with high traffic levels.

3.2. Discussions

According to the metrics, the correct operation of the “MultiColl-DCRN App” is identified, the tool presents coherent and relevant results for the analysis of spectral mobility, its multiple characteristics allow different scenarios to be worked on simultaneously. Through this tool, problems associated with decision making, multi-user access, collaborative scenarios and decentralized architectures can be studied.

For the analysis of the collaborative module, the VIKOR decision-making model and the naïve Bayes prediction technique are used at four levels of collaboration. It is identified that the best performance is presented for the highest levels of collaboration, in the case of the metrics associated with the predictions, the highest number of interference and perfect handoffs are for the lowest levels of collaboration, for the anticipated handoffs the lowest performance is for the highest levels of collaboration.

For the multi-user module analysis, the FFAHP decision-making model is used for six multi-user structures in conventional mode and in real mode. An increase in the performance of FFAHP is identified in terms of the number of users, the performance in real mode is lower than the conventional mode, this characteristic is due to the fact that the incorporation of random users in the real mode reduces the spectral opportunities and therefore they are more difficult to locate.

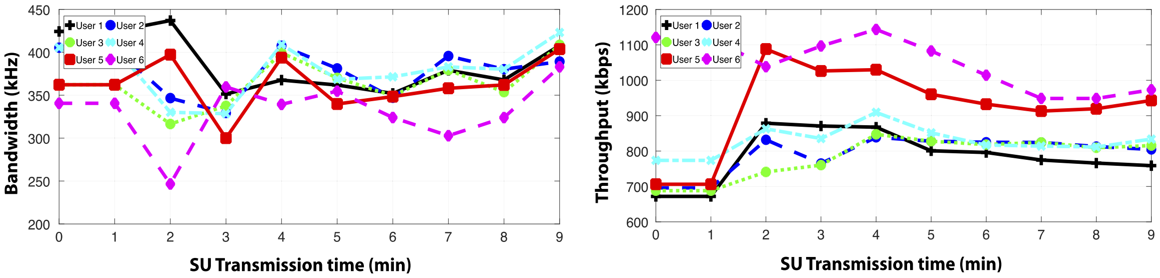

Figure 10. Bandwidth and throughput for the non-predictive SAW model with multi-user (real mode)

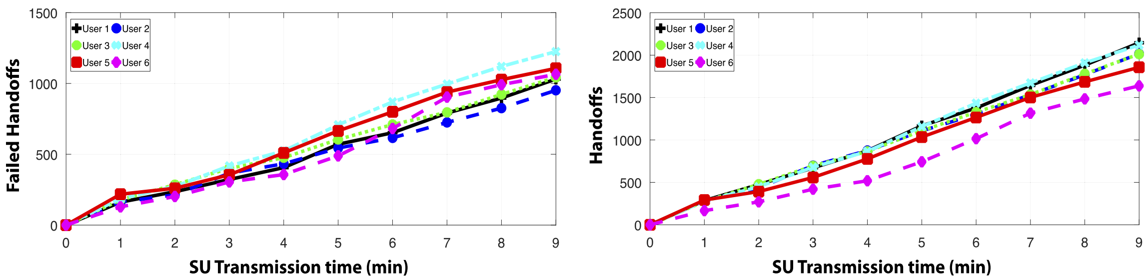

Figure 11. Failed handoffs and total handoffs for the non-predictive SAW model with multi-user (real mode)

4. CONCLUSION

This work presented the MultiColl-DCRN app which is a simulator for spectral mobility analysis in CRN with decentralized architectures, the tool was designed under a seven-module architecture which includes collaborative analysis, multi-user parameterization and six decision-making models. The operation of the MultiColl-DCRN app is validated through a set of simulations in collaborative scenarios and multiple user access, the throughput level, the number of failed handoffs, the number of handoffs, the number of handoffs with interference, the number of anticipated handoffs and the number of perfect handoffs. The present development represents a significant contribution to the cognitive radio network field given that there is currently no software available that encompasses all the mentioned features: collaboration between secondary users, cooperative decision-making, participation of multiple secondary users in spectral decision and decentralized networks.

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