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RESEARCH ARTICLE

Novel Methodological Proposal for Decision-Making in Decentralized Cognitive Radio Networks Based on Information Exchange Between SU

DIEGO ARMANDO GIRAL-RAMÍREZ[1], CESAR AUGUSTO HERNÁNDEZ-SUAREZ[1], AND INGRID PATRICIA PÁEZ PARRA[2]

[1]Ingeniería Eléctrica, Facultad Tecnológica, Universidad Distrital Francisco José de Caldas, Bogotá 111931, Colombia
[2]Departamento de Ingeniería de Sistemas e Industrial, Universidad Nacional de Colombia, Bogotá 111321, Colombia

Corresponding authors: Diego Armando Giral-Ramírez (dagiralr@udistrital.edu.co) and Cesar Augusto Hernández-Suarez (cahernandezs@udistrital.edu.co)

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ABSTRACT Cognitive Radio Networks (CRN) is a technology that avoids inefficient spectrum allocation and ensures efficient spectrum use. So, four processes are implemented: detection, analysis, decision-making, access, and adaptation. Despite the relevance of decision-making, it has not been explored to the same extent as the other processes. In CRNs, the decision-making process is developed according to the network architecture: centralized, distributed, and decentralized. Decentralized Cognitive Radio Networks (DCRN) are a hybrid model that uses the advantages of centralized and distributed networks simultaneously. Decentralized architectures have the infrastructure and are easy to implement. This decentralized approach is chiefly efficient for large networks and is considered the best option for public safety networks and social networking services. In order to address the challenges associated with DCRN decision-making and contribute to developing more effective approaches, this paper proposes a novel methodology for DCRN decision-making. A simulation environment for DCRN based on actual spectral occupancy data is developed, the performance of three Multi-Criteria Decision-Making Techniques (MCDM) in such a simulation environment is analyzed, and an information-sharing strategy between users is proposed. In order to assess the performance, two QoS metrics were used: the cumulative number of handoffs and the cumulative number of failed handoffs. The results obtained display a balance in which all users benefit. Although not all users get the maximum gain, all users contribute to reducing the number of channel changes and decreasing interference with other users.

INDEX TERMS Cognitive radio, cooperative systems, decentralized architecture, decentralized cognitive radio networks, multi-criteria decision-making techniques.

I. INTRODUCTION

A. GENERAL CONTEXT

In recent years, it has been observed that regulations granting exclusive licenses for the use of bands have generated problems of congestion, high demand, overuse, and underuse, among others. One way to reduce the issues generated by exclusive licenses is the shared use of radio access through CRNs [1]. The CRNs aim to allow Secondary Users (SU) access to licensed bands as long as they are not being used by Primary Users (PU). Cognitive communication has experienced rapid growth as a promising technology to overcome the challenges of the exclusive licensing model to meet the growing demand for high data rate services [2].

Four processes- detection, analysis, decision-making, and access- must be implemented to meet the goal of CRN. These processes work together and are continuously and dynamically repeated. This set of processes is known as the

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cognitive cycle. It enables a wireless network to use the radio spectrum efficiently and flexibly, optimizing capacity and minimizing interference.

The decision-making process allows the selection of the most appropriate spectral opportunity according to the requirements of the SUs and the environmental conditions. An incorrect decision-making process can affect the network's Quality of Service (QoS) indicators. However, despite its relevance, decision-making has not been explored. In CRNs, the decision-making process is developed according to the network architecture (Fig. 1), which can be classified into architecture with infrastructure or without infrastructure [3], [4].

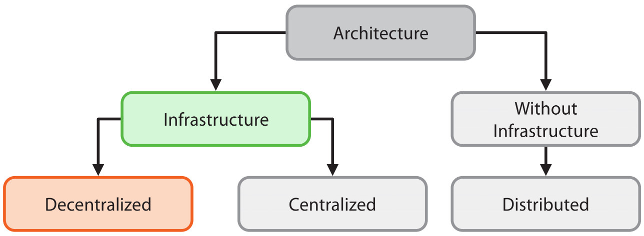

FIGURE 1. CRC architecture [5], [6].

In centralized architectures (Fig. 2(a)), there is a coordinator called a central entity (CE) or base station (BS), which is in charge of coordinating, assigning, and making channel decisions. The BS fulfills storing and processing the information delivered by the PUs and SUs [7]. The vulnerability of this architecture lies in the fact that the destruction of the central node causes a general loss of the system. Distributed networks form a mesh (Fig. 2(b)); the nodes of each subsystem share information; they can move freely, and there is no responsibility in the global coordination of licensed and unlicensed users, which allows this type of strategy to have a high application in networks where the implementation of infrastructure is not feasible [6], [8], [9], [10], [11]. The disadvantage of this model is its low security [12].

Decentralized networks are architectures formed by a set of centralized networks connected by additional links that create a mesh. Their structure incorporates the attributes of centralized and distributed networks, and Fig. 2(c) presents the hierarchy of a decentralized network. Decentralized architecture has an infrastructure; its implementation is simple, has good levels of security, an absence of communication overhead, lower delay, and low complexity, among others [13], [14]. A decentralized approach is an efficient option for large networks; moreover, it is the best alternative for social networking and public safety services [13], [15].

B. LITERATURE REVIEW

Three publications that work together with the two approaches are described: decentralized decision-making and architectures. In [17], the simulator App MultiColl-DCRN for spectral mobility analysis in decentralized architectures is presented. The tool allows the inclusion of collaborative

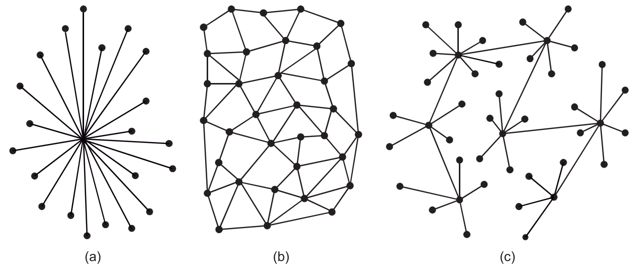

FIGURE 2. The architecture of a (a) centralized, (b) distributed, and (c) decentralized network [13], [16].

analysis and multi-user access. It has six decision-making models (one non-predictive and five predictive models); the metrics used are QoS indicators: number of handoffs, number of perfect handoffs, number of anticipated handoffs, number of handoffs with interference, number of failed handoffs, bandwidth, and throughput [15] propose a new decision-making policy for DCRN based on opportunistic spectrum access with radio frequency energy harvesting capabilities. The decision-making policies consist of three subunits: a sampling algorithm based on a Bayesian approach, an access scheme based on the Thompson sampling algorithm, and a mode selection scheme. The metrics obtained from the simulation process allowed us to identify that the analyzed policy offers a 10-35% improvement in DCRN throughput and a reduction in the subband switches of 40-90% compared to existing decision-making policies. [3] introduce optimization algorithms for decision-making in heterogeneous cognitive wireless networks. For DCRN, they propose a Hopfield-Tank neural network as a strategy. The proposal is validated through simulations to be implemented in an experimental cognitive system.

C. SCOPE AND CONTRIBUTIONS

The decision-making process in CRNs must be developed according to the network architecture. Decentralized networks distribute the responsibility of the information in different control points (nodes); they are architectures with infrastructure often confused with distributed networks. The general objective of this paper is to propose a methodology for decision-making in DCRN. The specific objectives are: first, propose a simulation environment for DCRN based on actual spectral occupancy data; second, analyze the performance of decision-making techniques in a DCRN simulation environment; and third, introduce an information exchange strategy between SUs. These objectives have been established to face the challenges generated in decision-making in DCRN and contribute to developing more effective approaches in this area.

The contribution of this work is presented in four elements. The first is the methodology used to model a DCRN. The second is the implementation of actual spectral power data for modeling the simulation environment. The third one is the proposal for information exchange between SUs; this strategy allows distributing the responsibility of the data in different control points, which is characteristic of decentralized networks. The fourth is the implementation of three multi-criteria strategies for decision-making. Although MCDM are widely used in various decision-making processes, current research does not present an analysis of these strategies for decentralized structures.

To ensure the reliability and consistency of the results in the decision-making process, the Combinative Distance-based Assessment (CODAS), Grey Relational Analysis (GRA), and Complex Proportional Assessment (COPRAS) techniques were implemented. However, it is relevant to note that the objective of this research is not to determine the best decision-making strategy. For the measurement of spectral power data, there is no decentralized network to collect information; therefore, considering that on a small range, a decentralized model behaves like a centralized architecture. The information was measured from a centralized network; the individual nodes will be characterized, and then connected. Although this approach may have limitations, it provides a basis for evaluating the performance of decision-making techniques and understanding their applicability in practical DCRN situations.

D. ORGANIZATION OF THE DOCUMENT

This work is presented in four sections, including the current section (introduction). Section II presents the methodology. Section III presents the results of the implemented case study and the respective discussion. Section IV presents the conclusions of the investigation and future work.

II. METHODOLOGY

Fig. 3 shows the stages of the methodology used to analyze the decision-making process in a decentralized cognitive radio simulation environment. The first stage, Spectrum Characterization, simulates the radio environment using a set of spectral power measurements obtained in an industrial and academic area. The second stage, Decentralized Architecture, is responsible for parameterizing and characterizing the DCRN architecture. The third stage, Spectral Decision-Making, carries out the decision-making process in which three multi-criteria techniques are implemented. Each phase of the methodology is described in detail below.

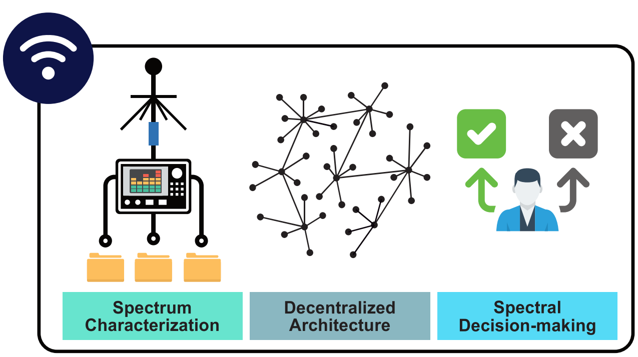

FIGURE 3. The methodology by stages for the decision-making process in a decentralized environment.

A. STAGE 1: SPECTRUM CHARACTERIZATION

[18] describe the methodology used for the environment design through experimental measurements. The general idea is to characterize the PU through real data from licensed users. To include real behavior, the spectral occupation is measured through the energy detection technique. From the measurement process, two matrices were constructed. One power matrix was used for training the implemented strategy, with dimensions of 10800 × 550 (rows × columns). The other power matrix validates the implemented approach with dimensions of 1800 × 550 (rows × columns). In these matrices, the rows represent time instants (each time instant is equivalent to 290 ms), and the columns represent the channels.

The Spectrum Characterization stage uses, as input parameters, the measured power matrix for training (10800 × 550) and, over a set of rules, transforms it into block segments. Fig. 4 presents the block diagram for the input and output variables of the Spectrum Characterization stage.

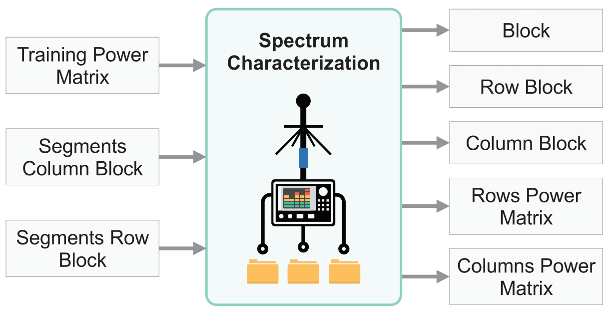

FIGURE 4. Spectrum characterization stage input and output variables.

The objective of this stage is to take the data from the measured power matrix for training and, according to a set of rules, group them to form blocks of rows and columns. Fig. 5 shows the structure of the blocks, where each block contains ordered information from the measured power matrix for model training.

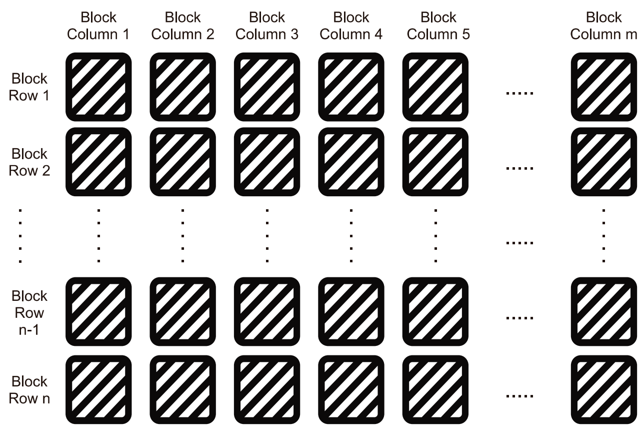

FIGURE 5. Structure by blocks row and blocks column measured power matrix.

Fig. 6 shows the structure of the block segments and the corresponding transformation rules. A block is an ordered segment of rows and columns of the spectral power matrix. All blocks have the same number of rows (Column Block) and the same number of columns (Row Block). The size of each block (Row Block × Column Block) depends on the proportional distribution that can be assigned according to the number of rows of the power matrix (Rows Power Matrix) and the number of columns of the power matrix (Columns Power Matrix).

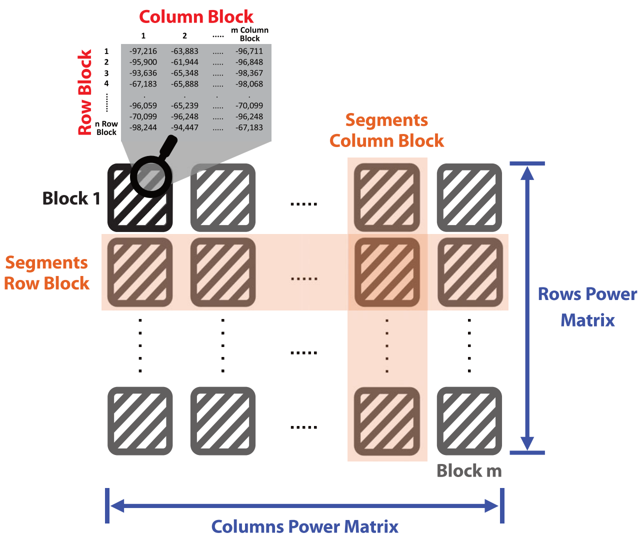

FIGURE 6. Structure of block segments and transformation rules.

Let's assume an example different from the case study to be analyzed in this research. It is desired to segment the training matrix into 27 blocks per column (Segments Column Block = 27) and 30 blocks per row (Segments Row Block = 30), for a total of 810 blocks (Block m = 810). For the row blocks, the distribution is an integer, so it is done straightforwardly. We have 10800 rows and are required to build 30 blocks per row, which means that the number of rows for each block must be 360 (Row Block = 360). However, for column blocks, the distribution is not an integer, so it is necessary to adjust the number of columns of the training matrix. If the distribution is done directly, for 550 columns and 27 blocks per column, the number of columns would be 20,3704 (Column Block = 20,3704).

To adjust this parameter and make the distribution straightforward, a strategy that eliminates columns until obtaining an integer ratio is implemented. In this case, it is necessary to eliminate ten columns from the training matrix. If we originally had 550 columns in the power matrix and then we removed ten columns, we obtained 540 columns. With these 540 columns and the need to build 27 blocks per column, the number of columns for each block should be 20 (Column Block = 20).

Fig. 7 describes the final result of the *Spectrum Characterization* stage when the training matrix needs to be segmented into 27 blocks per column and 30 blocks per row. Table 1 summarizes the final segmentation rules and parameters for the proposed example.

TABLE 1. Rules and final parameters for the *spectrum characterization* stage segmentation example.

	Rule	Final Parameter
Input	Segments Column Block	27
	Segments Row Block	30
Output	Rows Power Matrix	10800
	Columns Power Matrix	540
	Blocks	810
	Row Block	360
	Column Block	20

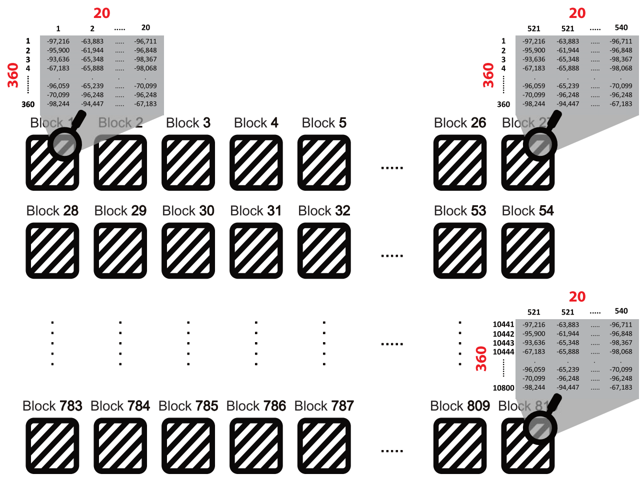

FIGURE 7. Stage spectrum characterization for 27 blocks per column and 30 blocks per row.

B. STAGE 2: DECENTRALIZED ARCHITECTURE

The objective of this stage is to define the number of nodes, their size, and the number of users per node for the DCRN. The *Decentralized Architecture* stage uses as input data the parameters of the *Spectrum Characterization* stage and the characteristics of the nodes (number, dimensions, and users). Fig. 8 presents the block diagram for the input and output variables of the *Decentralized Architecture* stage.

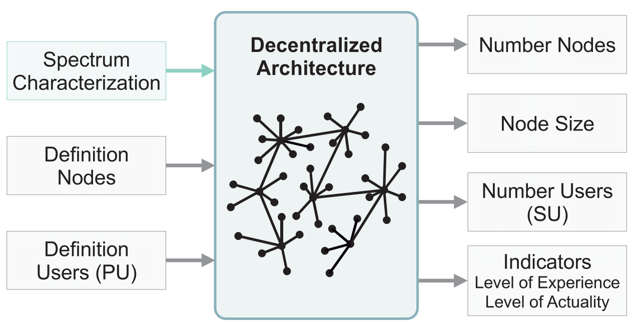

FIGURE 8. Input and output variables decentralized architecture stage.

1) NODE DEFINITION

According to the segmentation of Stage 1, a node is defined as the number of continuous column blocks. A node is characterized by the number of column blocks and the dimensions of each block. An architecture with centralized infrastructure is a network with a single node (Nodes Number = 1), and its diameter corresponds to the maximum number of column blocks (Node Size = Blocks Column m). An architecture with decentralized infrastructure is a network with multiple nodes (Nodes Number ≠ 1) where the size of each node is defined according to the requirements of the network. For this research, the size of each of the nodes was defined as a proportional ratio (k_n) of the maximum number of column blocks (Node Size = (k_n)*(Blocks Column m)).

Considering a second example is different from the case study to be analyzed in this research. It is required to segment the training matrix into nine blocks per column (Segments Column Block = 9) and five blocks per row (Segments Row Block = 5), for a total of 45 blocks (Block m = 45). Fig. 9 describes the characterization of the network if the architecture to be implemented is centralized; for this scenario, we have a single node (Node A) with Node Size = 9. Fig. 10 describes the characterization of the network if the architecture to be implemented is decentralized. For this scenario, we have three nodes (Node A, Node B, and Node C). For the size of the nodes, we assign a proportional relationship k_n = [0.22 0.44 0.33]; therefore, Node Size = [2 4 3].

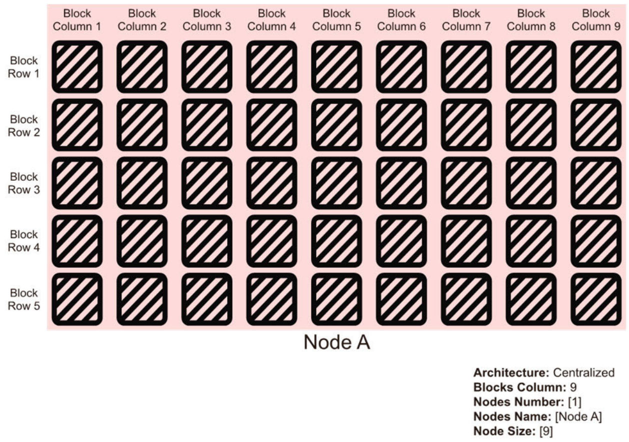

FIGURE 9. Characterization of a centralized network (Nodes Number = [1], Node Size = [9]).

2) DEFINITION OF USERS

Unlike conventional networks, there are two types of users in CRNs: PUs, who make licensed use of the frequency bands, and SUs, who make opportunistic use of the licensed spectrum as long as it is available. For this research, the characterization of PUs is performed by incorporating actual information obtained through experimental measurements. The characterization of the SUs is performed using the PU information access rules.

SUs have limited access to PU information; however, SUs can share the obtained information with other SUs. The objective is to analyze how the exchange (collaboration or

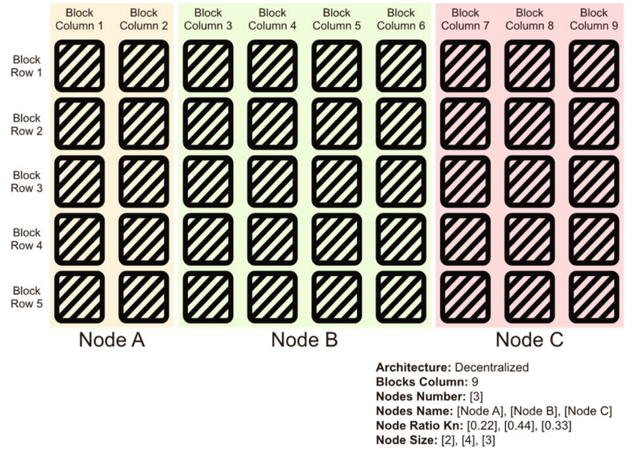

FIGURE 10. Characterization of a decentralized network (Nodes Number = [3], Node Size = [2], [3], [4]).

cooperation) of data among SUs affects decision-making. It is important to highlight two elements: first, the SUs only have access to a part of the PU information; they will never know the complete information; second, the decision-making process is the responsibility of the SUs and starts when the SUs enter and recognize the PU information, i.e., the PUs only provide the characterization of the radio environment.

- *Definition of the PU*

To characterize the PU behavior within the simulation environment, we performed measurements of the radio environment. The measured data corresponds to the spectral power over 60 minutes. It would be a mistake to assume that during the measurement time, the radio environment was used by a single PU and that the transmission requirements always presented the same behavior.

Furthermore, although observation and global knowledge of the network have advantages, it is not the most suitable option for large-scale systems and applications in public safety CRNs. This is due to the increased measurement costs, the complexity of the system, and the amount of information to be managed. Additionally, there is an imbalance and potential chaos if the base station fails [18].

To include a greater number of actual characteristics in the simulation environment during the 60 minutes, the knowledge of the information per node will not be global. One or more PUs may exhibit different behaviors, may or may not transmit data, may or may not change channels, and may require more or less transmission time.

As described above, to ensure that the knowledge of the information per node is not global, each node is divided into sub-blocks. This division not only limits access to global data but also allows for the characterization of multiple PUs with different behaviors in time and channels (columns). Fig. 11 describes the methodology to restrict access to information, using as an example the scenario proposed in Fig. 10. For each node, we selected a set of sub-blocks; this selection is random and adjusted according to the maximum number of blocks per node.

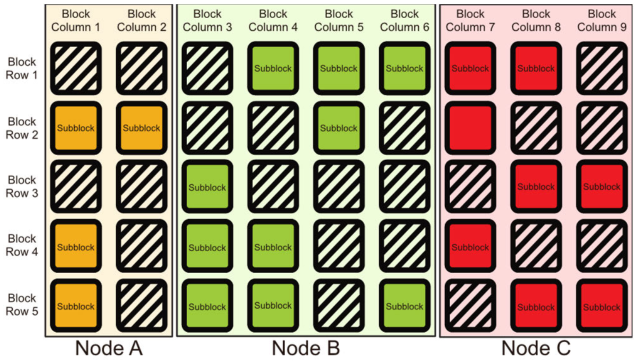

FIGURE 11. Methodology for limiting access to information and description of sub-blocks.

- *Definition of the SUs*

PUs provide the radio environment through the construction of nodes and sub-blocks (Fig. 11). The SUs take the characterized information from the PU and, through the information exchange and decision-making process, establish the frequency channel that is used opportunistically. To ensure that SUs make the best decision, they are assigned three access rules: amount of SUs per node, experience level indicator and topicality level, and interconnection of nodes. The following sections describe each of the characteristics defined in this work.

3) AMOUNT OF SUS PER NODE

In the simulation environment, SU is defined as a set of connected sub-blocks. In order to determine the number of SUs per node, it is necessary to identify and count the sets of connected subblocks per node. The rules for determining whether an array is connected are based on the connection between vertices. We used image processing to establish the number of SUs per node.

Fig. 12 describes the connectivity rules; sub-blocks are considered connected if they share edges or vertices. Two or more contiguous subblocks are part of the same SU if they meet and are connected in horizontal and vertical directions (Fig. 12 (a)). Two or more contiguous subblocks are part of the same user if they meet and are connected in horizontal or vertical directions (Fig. 12 (b)). If the sub-blocks are only connected diagonally, they are not part of the same user and are considered multiple users (Fig. 12 (c)).

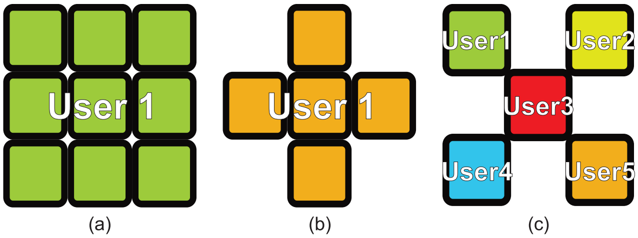

FIGURE 12. Connectivity rules between vertices to establish the number of users.

Fig. 13 shows the number of SUs for each node according to the connectivity rules between vertices for the scenario proposed in Fig. 10. For Node A, the number of SUs is 2. For Node B, the number of SUs is 3. And, for Node C, the number of SUs is 4.

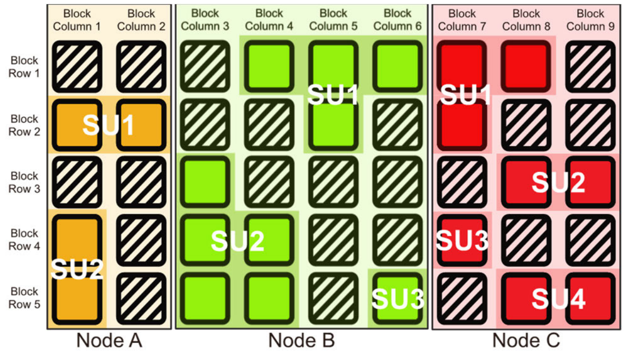

FIGURE 13. Number of SUs per node according to the connectivity rules between vertices.

4) LEVELS OF EXPERIENCE AND TIMELINESS INDICATORS

When two or more SUs share information, in addition to the data exchange methodology, it is required to analyze the relevance of the shared information; the data of one SU may be more relevant than the one from another SU. The relevance of the information may vary depending on different factors, such as the level of experience of the SU, the quality of the data, or the timeliness of the information.

In order to classify, differentiate, and establish the relevance of the type of information shared, two indicators are proposed in this research: the level of experience of the SU and the level of timeliness of the information known to the SU. These indicators are intended to allow the sharing to be fair, adequate, equitable, and prioritized according to the characteristics of the data.

Each SU, identified through the connection rules, is assigned an experience level indicator and a timeliness level indicator; these indicators, with the decision-making techniques, will be used to calculate the final DCRN channel score.

The experience level indicator is quantified according to the amount of knowledge of the SU. A high level of experience indicates that the SU is formed by a large number of sub-blocks, which implies that the information shared is more relevant compared to an SU that has a smaller number of sub-blocks. The timeliness level indicator is quantified according to the temporality of the shared data. A high level of timeliness indicates that the SU knows information from the most recent instants of the transmission, which implies that the information shared is more relevant in contrast to an SU that has information from the first instants of time. The methodology used to determine the two indicators is described below.

- *Level of experience and timeliness indicators*

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- *Level of experience indicator*

This indicator is based on the amount of information the SU knows. A numerical value is assigned, where the higher value represents a higher experience level. As shown in Equation (1), the SU experience level is directly proportional to the number of sub-blocks that make up the SU and inversely proportional to the total number of sub-blocks per node. Fig. 14 shows the flow chart for the experience level indicator. For this research, four (4) levels of experience were defined. A level four (4) experience is given to an SU composed of more than 75% of the sub-blocks of the node. A level 1 experience is assigned to an SU with less than 25% of the sub-blocks of the node. The remaining experience levels are assigned to an SU that consists of between 25% and 75% of the sub-blocks of the node.

$$Experience\ Levels_{SUn} = \frac{Subblocks_{SUn}}{\sum Subblocks_{Node}} \quad (1)$$

- *TimelinessIndicator*

This indicator is based on the currency of the information known by each SU. A numerical value is assigned, where the highest value represents that the SU has the most recent data. The timeliness indicator is proportional to the position of the sub-blocks. Considering that the rows of the sub-blocks represent instants of time, the highest timeliness indicator is assigned to the SUs located in the last blocks of rows and the lowest timeliness indicator is assigned to the SUs located in the first blocks of rows.

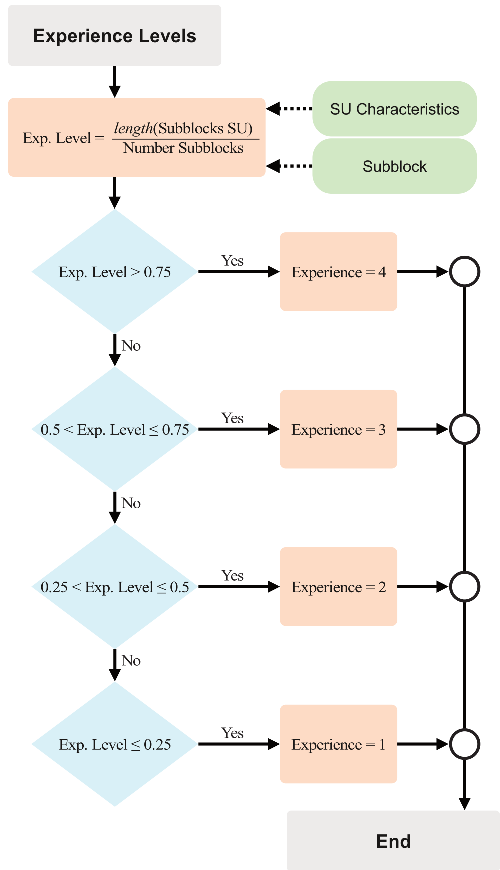

FIGURE 14. Experience level indicator flowchart.

Fig. 15 shows the analysis of the timeliness indicator of an example node. The process consists of three steps. The first step is to define the number of timeliness levels. In the proposed example in Fig. 15, three timeliness levels are assumed. For this research, we defined ten (10) experience levels.

The second step is to distribute the timeliness levels in the column blocks. The example node in Fig. 15 is divided into six column blocks. Therefore, the quotient between the column blocks and the timeliness levels would indicate that every two column blocks have one timeliness level. The lowest levels are found in the first instants of time (first blocks), while the highest levels are in the last instants of time (final blocks).

The third step consists of assigning each SU a timeliness level. SU1 is assigned timeliness level one (1). For this type of scenario, by design criteria, the timeliness level is assigned according to the highest position so SU2 is assigned timeliness level three. SU3 is located between timeliness levels two and three; thus, SU3 is assigned timeliness level three.

5) NODE INTERCONNECTION

Nodes act as a source of information and collaborative relaying; unlike classical systems, it is a bidirectional

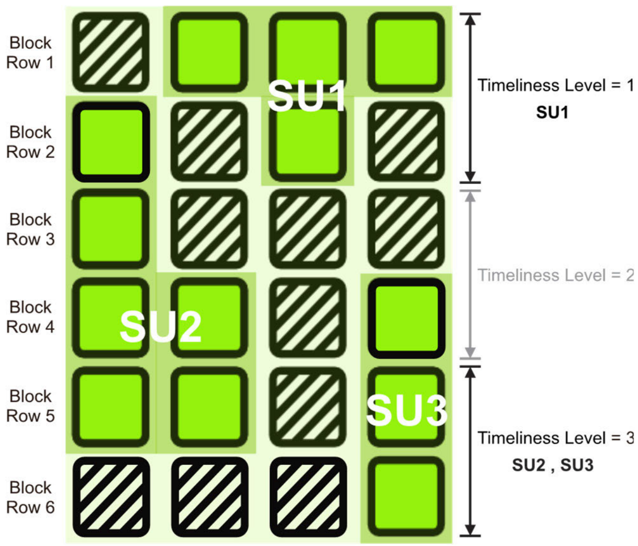

FIGURE 15. Timeliness indicator methodology.

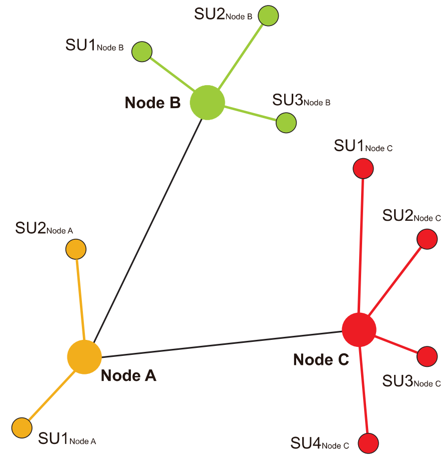

FIGURE 16. Decentralized architecture and cooperative structure.

information structure that saves energy. Cooperative CRNs can increase transmission speed and improve the indicators of QoS [18]. In the CRN, collaboration techniques allow users to exchange locally measured information. [19].

Fig. 16 depicts the structure and interconnection of the nodes for the decentralized architecture of the scenario proposed in Fig. 13. Each node (Node A, Node B, Node C) acts as a central unit responsible for coordinating, storing, and enabling the exchange of SU performance information with the other nodes in the architecture.

Each SU classifies the channels according to the information obtained on the behavior of the SUs and sends the information to the corresponding node through the control channel. The node or central unit analyzes the information received, determines the presence of the SU, and disseminates the decision to the other nodes. The decentralized architecture allows efficient exchange of information among the nodes and simplifies the decision-making regarding the presence of the SUs in the radio environment and the choice of the frequency channel with the best parameters to be used by the SU.

It is important to note that the connection order between nodes is an assumption. In this study, the connection order impact between nodes was not analyzed; it is assumed that the metrics are not affected if the connection changes. The analysis of this characteristic is beyond the scope of this research and can be part of a further study.

C. STAGE 3: SPECTRAL DECISION-MAKING

The decision-making process for the DCRN is performed through a five-stage structure. Fig. 17 shows the graphical representation of this structure. The following sections describe each of the stages in detail.

The first stage, "Availability Matrix," transforms the PU power data into binary values. In the second stage, called "Decision Vectors," the decision criteria of the MCDM for the SUs are calculated. During the third stage, called "Decision-making Techniques," the MCDM are implemented to obtain the SU channel scores.

Considering the last two stages, scores and metrics are calculated for each node individually, considering the local information of each SU. Additionally, scores and metrics can be obtained by studying the interaction between the DCRN nodes. In the fourth stage, called "Node Score and Network Score," the scores of the SU channels are taken, along with the indicators of experience level and timeliness level, to calculate the scores of each node and the scores considering the interaction between the DCRN nodes. Finally, in the fifth stage, called "Evaluation Metric," the performance metrics are generated.

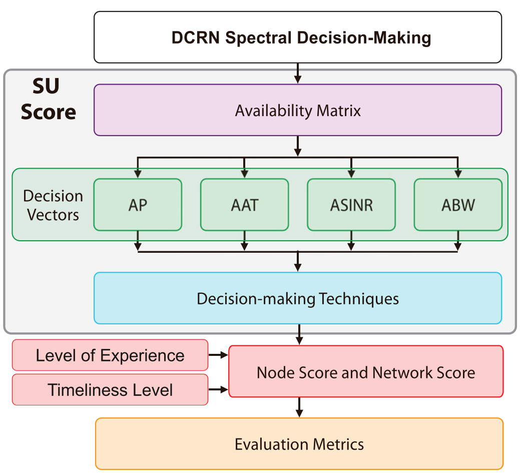

FIGURE 17. DCRN spectral decision-making stages.

1) NODE INTERCONNECTION

The selection of the best opportunity is performed using the spectral availability matrix. This matrix is obtained by transforming the radio environment to binary values according to the restriction given by the Threshold value (power threshold above which a PU is presented). In this transformation, the value one (1) is assigned to the available frequencies and the value 0 to the unavailable frequencies. [18] describe the methodology used for the transformation from spectral power to spectral availability. Algorithm 1 presents the programming structure implemented to obtain the training availability matrix.

Algorithm 1 Availability matrix structure

If Power Evaluation Traffic PU > Threshold
    Evaluation Availability PU = 1
else
    Evaluation Availability PU = 0
end

2) DECISION VECTORS

The MCDM depends on the decision criteria and their respective value; for this study, we selected four decision criteria: AP, AAT, ASINR, and ABW. Fig. 18 shows the meaning of each acrony; these criteria were chosen because they can be easily and efficiently obtained from the availability matrix.

The objective is to use these decision criteria to construct a matrix of scores for each of the SUs. Equation (2) presents the matrix of scores, with a size of *mx4*, and corresponds to the decision criteria calculated for each channel. The column vector is the weights assigned to each decision criterion; these weights must be normalized and set according to the priority and the evaluation criterion.

For this study, the same weight was assigned to each criterion, with a value of $\mathrm{W_{AP}} = \mathrm{W_{AA}T} = \mathrm{_{WASINR}} = \mathrm{W_{AB}W} = 0.25$. Equation (3) shows the general form of the scoring matrix;X_{NM} is the decision criteria, and ω_M is the weights.

$$[\mathrm{Score}]_{\mathrm{mx4}} = \begin{bmatrix} \mathrm{AP_{n,1}} & \mathrm{AAT_{n,1}} & \mathrm{ASINR_{n,1}} & \mathrm{ABW_{n,1}} \\ \mathrm{AP_{n,2}} & \mathrm{AAT_{n,2}} & \mathrm{ASINR_{n,2}} & \mathrm{ABW_{n,2}} \\ \vdots & \vdots & \vdots & \vdots \\ \mathrm{AP_{n,m}} & \mathrm{AAT_{n,m}} & \mathrm{ASINR_{n,m}} & \mathrm{ABW_{n,m}} \end{bmatrix} \times \begin{bmatrix} W_{AP} \\ W_{AAT} \\ W_{ASINR} \\ W_{ABW} \end{bmatrix} \tag{2}$$

$$x = \begin{bmatrix} x_{11} & \cdots & x_{1M} \\ \vdots & \ddots & \vdots \\ x_{N1} & \cdots & x_{NM} \end{bmatrix}, \omega = \begin{bmatrix} \omega_1 \\ \vdots \\ \omega_M \end{bmatrix} \tag{3}$$

- *Availability Probability (AP)*

The AP decision criterion refers to the normalized duty cycle analysis of each of the possible spectral opportunities. The AP result is a vector in which each element represents the average of the respective column of the availability matrix. The AP per channel is determined using Equation (4), where the "Spectral Opportunities" are defined by assigning the value 1 to the available frequencies.

$$\mathrm{AP_{Channels}} = \frac{1}{\text{Total time}} \sum \text{Spectral Opportunities} \tag{4}$$

- *Average SINR (ASINR)*

Th SINR decision criterio refers to the average difference between the signal power and the noise floor. For each non-zero element in the availability matrix, we calculated the difference between the element having the same position in the power matrix and the average value of the noise floor.

- *Average Bandwidth (ABW)*

The AB decision criterion refers to the average bandwidth (BW) of each spectral opportunity. However, since all channels have the same BW, the average will always be the same, which detracts from the importance of this criterion as an individual measure. For the BW variable to have an impact on the decision, a strategy was used in which up to four adjacent channels were considered, both to the left and right of each spectral opportunity. Only those channels that were available consecutively, i.e., that did not have channels occupied between them, were considered.

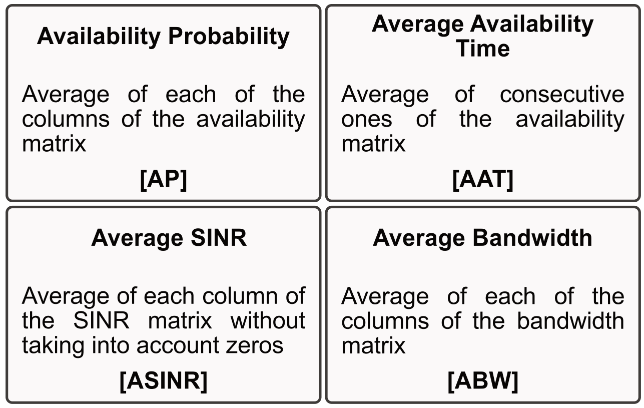

FIGURE 18. Description of the decision criteria used for the MCDM.

3) DECISION-MAKING TECHNIQUES

Equation (2) establishe a proportionality relationship between the decision criteria and the assigned weights. However, to identify the SU channels with the best spectral opportunities, it is necessary to assign a score that allows the channels to be ranked from the best to the worst. The assignment of the channel scores is performed using MCDM, a mathematical strategy widely used in decision-making processes [19], [20], [21], [22] In the same way, three MCDMs were implemented: CODAS, COPRAS, and GRA. It is important to note that the objective of this research is not to determine the best decision-making strategy. However, implementing the three techniques mentioned above guaranteed a more complete evaluation with reliable and consistent results. The mathematical structure of each of these techniques is described below [23], [24]

- *Combinative Distance-based Assessment (CODAS)*

It is a method based on the combinatorial distance; to determine the best alternative, it calculates Euclidean and

Taxicab distance. The best alternative is the one that has the greatest distance from the negative ideal solution [25], [26]. The steps for CODAS are described below.

The first step is to normalize Equation (3) according to Equation (5), where N_b and N_c represent the series of benefit (maximize) and cost (minimize) criteria.

$$n_{ij} = \begin{cases} \dfrac{x_{ij}}{\max\limits_{i} x_{ij}} & \text{if } j \in N_b \\ \dfrac{\min\limits_{i} x_{ij}}{x_{ij}} & \text{if } j \in N_c \end{cases} \tag{5}$$

The second step is to calculate the normalized weighted decision matrix using Equation (6).

$$r_{ij} = w_j n_{ij}$$
$$\sum_{j=1}^{m} \omega_j = 1 \tag{6}$$

The third step is to determine the negative ideal solution according to Equation (7).

$$\text{ns} = \left[\text{ns}_\text{j}\right]_{1xm} \text{ where } \text{ns}_\text{j} = \min_{i} r_{ij} \tag{7}$$

The fourth step is to calculate the Euclidean distances and Taxicab distances (Equation (8) and Equation (9)).

$$E_i = \sqrt{\sum_{j=1}^{m} \left(r_{ij} - \text{ns}_j\right)} \tag{8}$$

$$T_i = \sum_{j=1}^{m} \left|r_{ij} - \text{ns}_j\right| \tag{9}$$

The fifth step is to obtain the relative evaluation matrix according to Equation (10), Equation (11), and Equation (12), where $k \in \{1, 2, \ldots, n\}$ denotes a threshold function to recognize Euclidean equality. τ is the threshold parameter responsible for establishing the decision. This parameter should be set between 0.01 and 0.05. In this paper, it is assumed that $\tau = 0.05$ with variable u for the calculations.

$$R_a = [h_{ik}]_{n\times n} \tag{10}$$

$$h_{ik} = (E_i - E_k) + (\psi\,(E_i - E_k)\,x\,(T_i - T_k)) \tag{11}$$

$$\psi(x) = \begin{cases} 1 & if\,|x| \geq \tau \\ 0 & if\,|x| < \tau \end{cases} \tag{12}$$

The sixth step is to calculate the assessment score of each alternative according to Equation (13).

$$H_j = \sum_{k=1}^{m} H_{ik} \tag{13}$$

Finally, the seventh step is to rank the alternatives according to the decreasing assessment score values (H). The best option is the alternative with the highest H.

- *Complex Proportional Assessment (COPRAS)*

It is a method based on complex proportional analysis. Makes the ranking and assessment of decision alternatives based on their importance and usefulness. The overall score is obtained by combining the decision criteria weights and the individual scores of each channel [27], [28]. The steps for COPRAS are described below.

The first step is to normalize Equation (3) according to Equation (14).

$$r_{ij} = \frac{x_{ij}}{\max\limits_{j} x_{ij}} \tag{14}$$

The second step is to normalize the weighted decision matrix according to Equation (15).

$$E_{ij} = w_j r_{ij} \tag{15}$$

The third step determines the weighted average scores, where E_{+ij} and E_{-ij} are associated with the maximization criterion and the minimization criterion, respectively (Equation (16) and Equation (17)).

$$M_{+i} = \sum_{j=1}^{n} E_{+ij} \tag{16}$$

$$M_{-i} = \sum_{j=1}^{n} E_{-ij} \tag{17}$$

The fourth step is to establish the relative importance of the decision alternatives (Equation (18)).

$$Z_j = M_{+i} + \frac{\sum_{i=1}^{m} M_{-i}}{M_{-i}\left(\sum_{i=1}^{m} \frac{1}{M_{-i}}\right)} \tag{18}$$

Finally, the fifth step is to establish the decision alternatives' performance indices (Equation (19)), where the option with a utility rating of 100 is the best.

$$Z_i = \frac{V_i}{V_{\max}} \tag{19}$$

- Grey Relational *Analysis* (GRA)

It is based on the assumption that a system is uncertain and that information about the system is insufficient to construct a relational analysis or build a model to characterize the system [29], [30]. The steps for CODAS are described below.

The initial data must be normalized so that the first step is to standardize Equation (3). If minimization is convenient, the data are normalized using Equation (20). If maximization is opportune, the data are normalized using Equation (21).

$$r_{ij} = \frac{x_{ij} - \min\limits_{i\in M} x_{ij}}{\max\limits_{i\in M} x_{ij} - \min\limits_{i\in M} x_{ij}} \tag{20}$$

$$r_{ij} = \frac{\max\limits_{i\in M} x_{ij} - x_{ij}}{\max\limits_{i\in M} x_{ij} - \min\limits_{i\in M} x_{ij}} \tag{21}$$

The second step is to determine the Grey Relational Coefficient (GRC); in most cases, to evaluate multiple response characteristics, they are calculated using the average GRC value (Equation (22)).

$$\text{GRC}_i = \frac{1}{N} \sum_{j\in N} \frac{\Delta_{\min} + \Delta_{\max}}{\Delta_i + \Delta_{\max}} \tag{22}$$

The values $\Delta_{\max}$, $\Delta_{\min}$, andΔ_i are obtained from Equation (23), Equation (24), and Equation (25).

$$\Delta_{\max} = \max_{i\in M, j\in N} \Delta_i \tag{23}$$

$$\Delta_{\min} = \min_{i \in M, j \in N} \Delta_i \tag{24}$$

$$\Delta_i = \left| x_{0j} - r_{ij} \right| \tag{25}$$

Finally, in the third step, the best alternative is selected according to the GRC. The alternative with the highest GRC is considered the best option among them. This selection is done by implementing Equation (26).

$$A^*_{\mathrm{GRA}} = \arg\max_{i \in M} (\mathrm{GRC}_i) \tag{26}$$

4) NODE SCORE AND NETWORK SCORE

With the indicators of experience level, timeliness level, and the scores obtained by the MCDM for the SU channels, we determined the scores for each node and the scores considering the interaction between the DCRN nodes.

The scores for each DCRN node are determined through Equation (27), where $\mathrm{Score}_{\mathrm{Node(n)}}$ is the score for the channels of Node n; $\mathrm{Score}_{\mathrm{SUn}}$ is the score obtained for each SU of Node n; $\mathrm{K}_{\mathrm{SUn}}$ is a proportionality ratio determined for each SU of Node n, according to the indicators of experience level and timeliness level. Equation (28) describes how $\mathrm{K}_{\mathrm{Sun}}$ is calculated. In this equation, α and β are constants that are assigned to establish the priority of the indicators, where $\alpha + \beta = 1$.

The experience level and the timeliness level indicators are complementary and add value to the decision-making process when SUs exchange data. By considering both indicators, an effective process can be achieved. However, in environments where conditions can change rapidly, prioritizing the timeliness indicator offers benefits; it allows SUs to make decisions based on the latest information, which is especially valuable in CRN environments. Up-to-date data allows SUs to adapt to current environmental conditions quickly and accurately. Considering the benefits of prioritizing the timeliness indicator and the complementary contribution of experience levels, $\alpha = 0.7$ and $\beta = 0.3$ were assigned for this research.

$$\begin{aligned}\mathrm{Score}_{\mathrm{Node(n)}} = & K_{\mathrm{SU1}} [\mathrm{Score}_{\mathrm{SU1}}] \\ & + K_{\mathrm{SU2}} [\mathrm{Score}_{\mathrm{SU2}}] \\ & + K_{\mathrm{SUn}} [\mathrm{Score}_{\mathrm{SUn}}]\end{aligned} \tag{27}$$

$$\begin{aligned}K_{\mathrm{SUn}} = & \alpha\, (\text{Timeliness level})_{\mathrm{SUn}} \\ & + \beta\, (\text{Level of experience})_{\mathrm{SUn}}\end{aligned} \tag{28}$$

The scores for all DCRN channels are assigned considering the interaction between nodes and are determined using Equation (29). The methodology is similar to the calculation of the scores for each node; the difference is that for the network score, the information exchange of all the SUs in the network is considered

$$\begin{aligned}&\mathrm{Score}_{\mathrm{Network}} = \sum_{n=1}^{\text{Total SU}} K_{\mathrm{SUn}} \mathrm{Score}_{\mathrm{SUn}} \\ &\sum_{n=1}^{\text{Total SU}} K_{\mathrm{SUn}} = 1\end{aligned} \tag{29}$$

5) EVALUATION METRICS

In order to evaluate the performance, we used two QoS metrics: the cumulative number of handoffs and the cumulative number of failed handoffs. Table 2 shows the name, description, and type of metric evaluation. The two metrics are of cost type, which means that a lower number of handoff and failed handoff reflects a better result.

In the context of CRNs, a handoff is a process in which an SU switches from one channel (column) to another. This change can occur for different reasons, such as when interference occurs or when a better opportunity is identified. The handoff objective is to improve communication performance by taking advantage of the opportunities available in the radio environment. [18] describe in detail the methodology used to quantify the cumulative number of handoffs and the cumulative number of failed handoffs.

TABLE 2. Rules metrics used in the evaluation of the models.

Name	Description	Type of metric evaluation
Handoffs	Total number of handoffs performed during the SU transmission time	Cost
Failed Handoffs	The number of handoffs that the SU could not materialize because it found the respective target spectral opportunities occupied.	Cost

III. RESULTS

Performance metrics are generated using the power matrix for validation and the score obtained for each node and the DCRN. The results are divided into three sections. The first section shows the final structure of the DCRN. The second section presents the QoS metrics obtained for each node of the decentralized network. In that section, it is assumed that each node operates independently; therefore, the SUs only have access to the information associated with each node (Equation (27)). The metrics obtained for each SU are not presented because the number of simulations required is considerable, and the analysis performed per node is sufficient for this study. Additionally, the third section shows the QoS metrics obtained when the nodes of the decentralized network share information. In this configuration, the SUs exchange information; thus, the nodes do not operate independently (Equation (28)).

The proposed strategy was implemented in MATLAB - MathWorks R2023a with a license provided by Universidad Distrital Francisco José de Caldas (Bogotá, Colombia). The simulation process was carried out on a computer with a 2.8 GHz Intel(R) Core (TM) i7-7700HQ processor and 24 GB of RAM. The operating system used was Microsoft Windows 10 - 64 bits.

A. FINAL DCRN STRUCTURE

Table 3 describes the final characteristics of the implemented decentralized network. As mentioned in the methodology, each node was randomly divided into sets of sub-blocks to avoid a global knowledge of the information and to allow different performances in terms of timing and channels. In order to ensure that the results are not affected by the random creation of the sub-blocks, five simulations were performed, and the results obtained were averaged. Each simulation adjusts to the characteristics described in Table 3, varying only in the random generation of the sub-blocks.

TABLE 3. Characteristics of the implemented decentralized network.

Name	Description
Rows Power Matrix	10800
Columns Power Matrix	540
Blocks	810
Number of nodes	5
Segments Column Block	27
Segments Row Block	30
Number of blocks per node	[3 , 7 , 8 , 4 , 5]

Fig. 19 shows the distribution of the nodes, the blocks per node, and the randomly generated sub-blocks for the first simulation (simulation 1). The rows represent blocks of instants of time, and the columns represent blocks of channels (Fig. 6 shows the structure of the block segments and the corresponding transformation rules). The zeros (0) indicate that this block was not selected as a sub-block, while the ones (1) imply that this block was selected as a sub-block. To determine the number of SUs per node, we applied the connectivity rules of image processing; for example, in the case of Node 1 in Fig. 19, 14 SUs are identified.

Considering that the number of SUs per node is the parameter affected by the random selection of the sub-blocks, Table 4 shows the amount of SUs per node obtained for the five simulations performed (simulation 1, simulation 2, simulation 3, simulation 4, and simulation 5). In the last row of the table is the average to the largest integer of SU for each node.

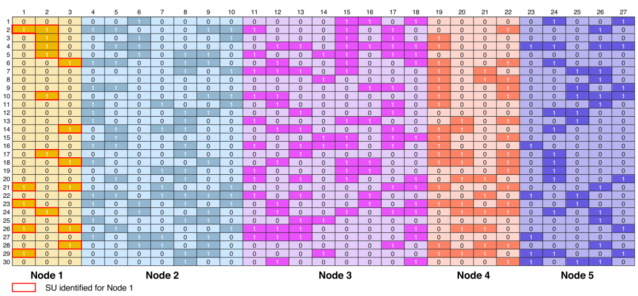

FIGURE 19. Blocks, nodes, sub-blocks, and SU for the first simulation.

According to the number of nodes presented in Table 3 and the average number of SUs per node described in Table 4, Fig. 20 shows the architecture of the implemented DCRN. It is relevant to highlight that the order of connection between nodes represented in Fig. 20 is an assumption. In this study, the connection order impact between nodes was not analyzed, and it is assumed that the handoff and failed handoff metrics are not affected if the connection changes; analysis of this feature is beyond the scope of this research and can be part of a further study.

TABLE 4. Characteristics of the decentralized network structure.

Simulation	SU by node
Simulation 1	[14 , 44 , 41 , 23 , 33]
Simulation 2	[14 , 53 , 51 , 22 , 32]
Simulation 3	[13 , 45 , 55 , 17 , 28]
Simulation 4	[12 , 37 , 57 , 26 , 20]
Simulation 5	[16 , 40 , 50 , 24 , 31]
Average SU	[14 , 44 , 51 , 22 , 29]

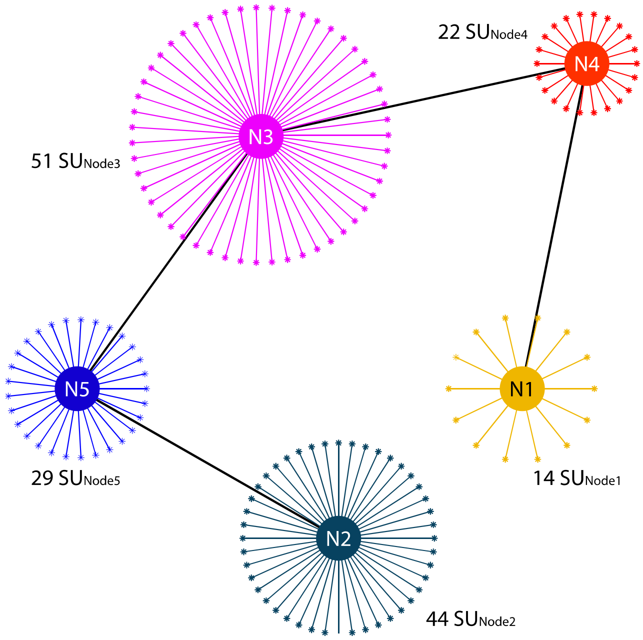

FIGURE 20. Structure of the implemented DCRN.

B. NUMBER OF HANDOFF AND FAILED HANDOFF PER NODE

This section presents the handoff and failed handoff metrics per node when using the MCDM CODAS, COPRAS, and GRA. The scenarios analyzed assume that the SUs only have access to the scores obtained by each node so that the nodes operate independently. The objective is not to determine which is the best decision-making strateg; all three techniques are used to ensure that the results are reliable and consistent.

1) NUMBER OF HANDOFFS ACCUMULATED PER NODE

Fig. 21, Fig. 22, and Fig. 23 show the cumulative number of handoffs per node during a 9-minute transmission when implementing the CODAS, COPRAS, and GRA decision-making models, respectively.

2) CUMULATIVE NUMBER OF FAILED HANDOFFS PER NODE

Fig. 24, Fig. 25, and Fig. 26 show the cumulative number of failed handoffs per node during a 9-minute transmission when

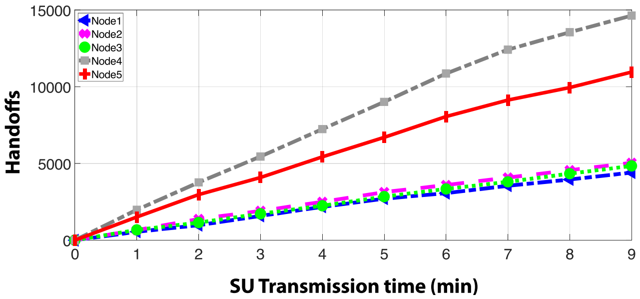

FIGURE 21. Number handoffs per node using CODAS.

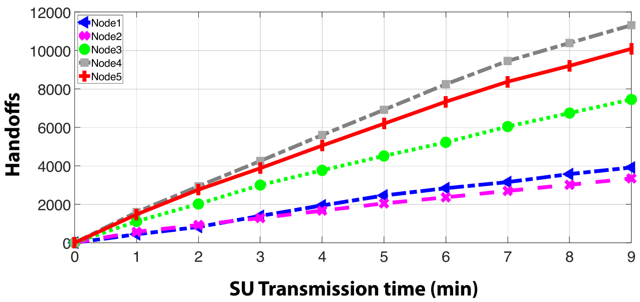

FIGURE 22. Number handoffs per node using COPRAS.

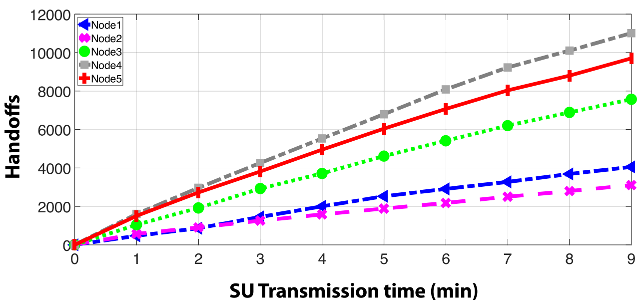

FIGURE 23. Number handoffs per node using GRA.

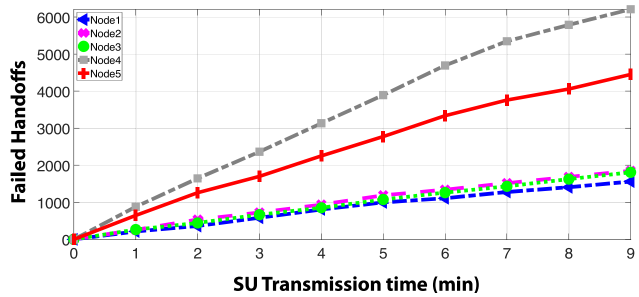

FIGURE 24. Number of failed handoffs per node using CODAS.

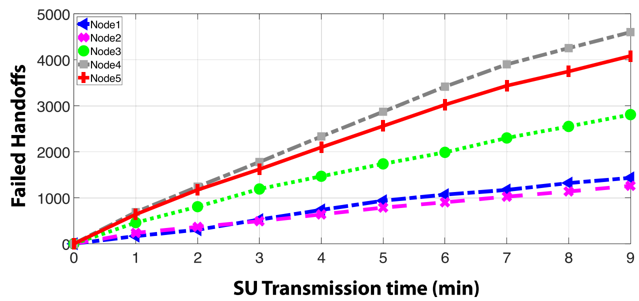

FIGURE 25. Number of failed handoffs per node using COPRAS.

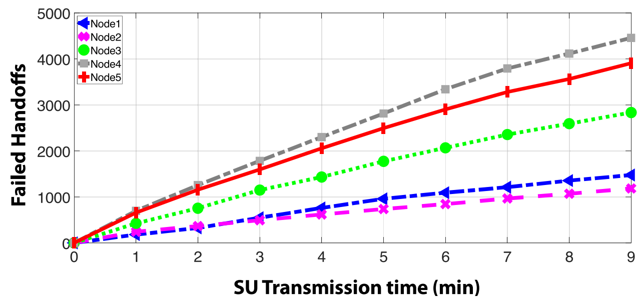

FIGURE 26. Number of failed handoffs per node using GRA.

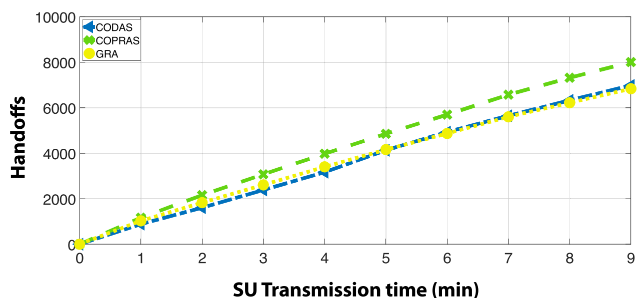

FIGURE 27. Number of accumulated DCRN handoffs.

implementing the CODAS, COPRAS, and GRA decision-making models, respectively.

3) NUMBER OF HANDOFF AND HANDOFF FAILURES DCRN

This section displays the handoff and failed handoff metrics for the DCRN when using the MCDM, CODAS, COPRAS, and GRA. In the scenario analyzed, the SUs exchange information between nodes so that the nodes do not operate independently.

Fig. 27 shows the cumulative number of handoffs per MCDM during a 9-minute transmission. Fig. 28 shows the cumulative number of failed handoffs per MCDM during a 9-minute transmission.

C. DISCUSSION

To discuss the results obtained from the DCRN decision-making process based on the proposed exchange of information between SUs, the bar charts in Fig. 29 and Fig. 30 are presented. Fig. 29 describes the total handoffs obtained for minute 9. Fig. 30 describes the total failed handoffs obtained for minute 9. The results are contrasted per node, per MCDM, and according to the metrics obtained when the information exchange is performed.

Regarding the comparative analysis between nodes for the total handoffs presented in Fig. 29, since it is a cumulative cost metric, it is observed that the best results are obtained for Node 1 and Node 2. While the worst results are recorded for Node 4 and Node 5, Node 3 is located at an intermediate

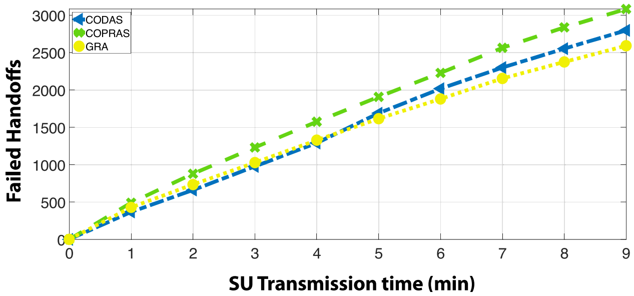

FIGURE 28. Number of cumulative DCRN failed handoffs.

point. Initially, it could be assumed that the low performance at Nodes 4 and 5 is related to the MCDM technique used. However, to ensure the reliability and consistency of the results in the decision-making process, it is sufficient to compare the metrics obtained per node between CODAS, COPRAS, and GRA. As can be identified in Fig. 29, the highest variation in the number of handoffs per node between the MCDM, with an average difference of 55.25%, is obtained in Node 3, compared to CODAS, which is the MCDM with the best result.

Fig. 30 supports the total number of handoffs analysis by considering the total number of failed handoffs. As in Fig. 29, for the comparative analysis between nodes, the best results are obtained for Node 1 and Node 2; the worst results are recorded for Node 4 and Node 5, with Node 3 falling in between. The highest variation in the metrics obtained per node between CODAS, COPRAS, and GRA, with an average difference of 55.86%, is obtained in Node 3, compared to CODAS, which is the MCDM with the best result.

Avoiding the low-performance relationship with the MCDM techniques for the number of total handoffs and the number of total failed handoffs, the analysis focuses on the availability characteristics of each network node. Based on the metrics obtained, it can be concluded that nodes 1 and 2 present the highest number of spectral opportunities. This result allows the SUs, through the multi-criteria decision-making process, to reduce the number of channel changes and the number of interferences. On the other hand, nodes 4 and 5 have the least number of spectral opportunities, increasing the number of channel changes and the number of interferences.

In Fig. 29 and Fig. 30, the bar chart titled ''Decentralized'' shows the metrics of the total handoffs and failed handoffs for minute 9 when the nodes do not operate independently and information exchange is performed between the SUs. As shown in Fig. 29 and Fig. 30, the metrics under the decentralized architecture are above those obtained for Node 1 and Node 2, and below those obtained for Node 4, Node 5.

Table 5 and Table 6 present the variation in the total number of failed handoffs and handoffs concerning the decentralized architecture. A positive value indicates an increase in the metric when working with a decentralized architecture. A negative value indicates a decrease in the metric when working with a decentralized architecture. This analysis allows for the identification of the advantages and disadvantages of implementing a DCRN. As a disadvantage, an increase in the number of handoffs and failed handoffs is observed compared to nodes that have a larger number of spectral opportunities. However, as an advantage, a decrease in the number of failed handoffs and handoffs is achieved compared to nodes that have a lower number of spectral opportunities. In other words, a DCRN allows the establishment of a win-win equilibrium. Although, individually, not all SUs obtain the maximum gain, all SUs contribute to reducing the number of channel changes and decreasing interference with the other SUs.

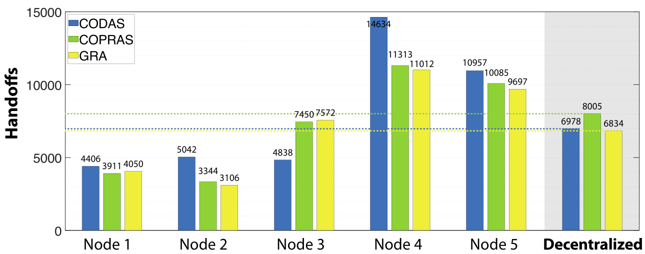

FIGURE 29. Total number of handoffs.

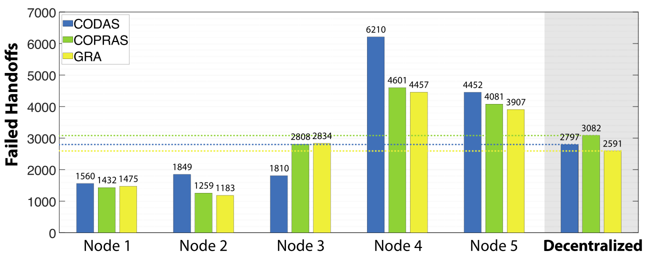

FIGURE 30. Total number of failed handoffs.

TABLE 5. Variation in the number of total handoffs per node concerning information exchange.

Node	CODAS	COPRAS	GRA
Node 1	2572	4094	2782
Node 2	1936	4661	3728
Node 3	2140	555	-738
Node 4	-7656	-3308	-4178
Node 5	-3979	-2080	-2863
Node 1	2572	4094	2782

TABLE 6. Variation in the number of failed handoffs per node concerning information exchange.

Node	CODAS	COPRAS	GRA
Node 1	1237	1650	1116
Node 2	948	1823	1408
Node 3	987	274	-243
Node 4	-3413	-1519	-1866
Node 5	-1655	-999	-1316
Node 1	1237	1650	1116

IV. CONCLUSION

DCRN are a hybrid model that utilizes the advantages of both centralized and distributed networks. In order to address the challenges associated with decision-making in DCRN and contribute to building more effective approaches, an innovative methodology for DCRN decision-making based on information sharing between SUs was developed. This methodology incorporates actual information from the radio environment for the simulation of the radio environment, implements CODAS, COPRAS, and GRA multi-criteria strategies as decision-making techniques, and uses the cumulative number of handoffs and the cumulative number of failed handoffs during a 9-minute transmission as performance metrics.

The results obtained were compared by node, by MCDM, and according to information exchange. The results allowed us to identify a balance where all users benefit. Although not all users obtain the maximum utility, all users contribute to reducing the number of channel changes and, therefore, reducing interference with other SUs. These results demonstrate the effectiveness of the proposed methodology and its potential to improve the performance and efficiency of CRNs, supporting the importance of considering information sharing as a fundamental strategy and highlighting the need to develop new proposals to facilitate this sharing.

A. FUTURE WORK

As user requirements increase, research questions in the area of DCRN are growing exponentially; there are several challenges to be solved, and it is necessary to constantly propose new methodologies that allow the inclusion of a higher number of characteristics related to user performance and the radio environment, to improve efficiency, performance, and QoS indicators. In future research, it is recommended to explore new QoS metrics to evaluate the DCRN in terms of latency, interference, throughput, capacity, and reliability, among others. Also, consider indicators of information relevance in addition to the level of experience and timeliness. Propose decision-making strategies based on artificial intelligence or optimization strategies based on bio-inspired algorithms. Regarding information exchange, this study analyzed the exchange between SUs. However, it is necessary to analyze other cooperation strategies. Finally, evaluate these strategies in authentic environments.

B. APPLICATIONS

The fundamental objective of these strategies is to optimize the use of the radio frequency spectrum, as its efficient management contributes to socioeconomic progress, significantly improving the quality of life in communities. In the realm of social development, sound decision-making facilitates the expansion of Internet services in areas with unmet basic needs. In the healthcare sector, the creation of wireless networks for eHealth applications is promoted. Finally, in industry and services, the implementation of cognitive sensor networks for process monitoring is considered.

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DIEGO ARMANDO GIRAL-RAMÍREZ was born in Bogotá, Colombia. He received the bachelor's and master's degrees in electrical engineering. He is currently pursuing the Ph.D. degree in engineering with Universidad Distrital Francisco José de Caldas, Colombia. He is an Assistant Professor of electrical engineering programs with Universidad Distrital Francisco José de Caldas. His research interests include mathematical optimization, cognitive radio networks, power systems, automation, and intelligent systems.

CESAR AUGUSTO HERNÁNDEZ-SUAREZ was born in Villavicencio, Colombia. He received the bachelor's and master's degrees in electronic engineering and telecommunications from Universidad Distrital Francisco José de Caldas, Colombia, and the Ph.D. degree in engineering from Universidad Nacional de Colombia. He is currently a Titular Professor of electrical engineering programs with Universidad Distrital Francisco José de Caldas. His research interests include mathematical optimization, cognitive radio networks, and intelligent systems.

INGRID PATRICIA PÁEZ PARRA was born in Bogotá, Colombia. She received the bachelor's and master's degrees in electrical engineering from Escuela Colombiana de Ingeniería, Colombia, and the Ph.D. degree in engineering from Universidad de Cantabria. She is currently an Assistant Professor of system and industrial engineering programs with Universidad Nacional de Colombia. Her research interests include telecommunications, cognitive radio networks, and wireless networks.