Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ANALYSIS AND EVALUATION OF SPECTRAL DECISION WITH MULTI-USER ACCESS USING MARKOV CHAINS IN COGNITIVE WIRELESS NETWORKS

[1]DIEGO ARMANDO GIRAL-RAMÍREZ, [2]CESAR AUGUSTO HERNÁNDEZ-SUAREZ, [3]FREDY HERNAN MARTÍNEZ-SARMIENTO

[1,2,3] Universidad Distrital Francisco José de Caldas, Technological Faculty, Bogotá D.C, Colombia, 111931

E-mail: [1]dagiralr@udistrital.edu.co, [2]cahernandezs@udistrital.edu.co, [3]fhmartinezs@udistrital.edu.co

ABSTRACT

The increase in wireless applications, limited spectrum resources and the fixed allocation policy have caused the radioelectric spectrum to present shortage problems. Cognitive radio (CR) emerged as a solution to solve the problems of allocation and spectrum scarcity, it is a dynamic allocation technique, which identifies spectral opportunities and then automatically configures the system according to the electromagnetic environment. One of the most important aspects in cognitive radio networks (CRN) is the spectral decision function, which involves challenges and a high level of complexity, due to the need to work with real characteristics, such as multi-user spectral allocation and network externality. This work analyzes the decision-making process in CRN with multi-user access using Markov chains. The analysis is performed for the access of 3 users based on the number of total accumulated handoffs, number of total accumulated failed handoffs, average bandwidth, average delay, and average Throughput. The results show that the best performance is for the scenario with 1 user, the lowest performance is for the scenario with 3 users. The results obtained indicate that the users opportunistically used a greater bandwidth, maximizing the effective transfer capacity without affecting the transmission of the licensed users.

Keywords: *Cognitive Radio Networks, Decision-making Model, Markov Chains, Multi-user Access, Spectral Mobility*

1. INTRODUCTION

The growth of wireless applications poses new challenges in future communication systems, total mobile data traffic is expected to grow to 49 exabytes per month [1]–[5]. This, together with the fact that the current allocation policies are fixed and regulated by the state [6], has caused the radioelectric spectrum to present shortage problems.

CRN are a solution to solve the problems of fixed allocation and spectrum scarcity. CR requires the implementation of techniques based on optimization models, artificial intelligence, stochastic processes, complex systems, machine learning, deep learning, among others. In the CR there are two types of users, the user who accesses the frequency bands in a licensed way, called licensed or primary (PU), and the unlicensed or secondary user (SU) who uses the spectrum opportunistically [7], [8].

In order for spectrum to be used opportunistically, CRN work with a management model called the cognitive cycle and is shown in Figure 1. The model is characterized by four main functions: spectrum detection, spectrum decision , spectrum mobility and spectrum sharing [9], [10].

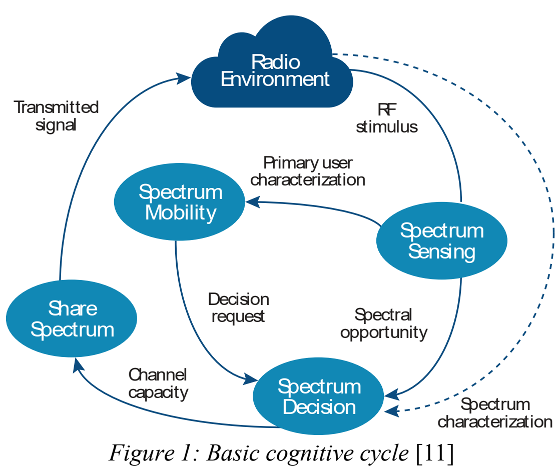

Figure 1: Basic cognitive cycle [11]

Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

In CRN, users make intelligent decisions based on the actions taken by other users, the probability that two or more users choose the same channel is high [12]. Therefore, to model the network under realistic traffic parameters, it is necessary to analyze simultaneous multi-user access [13], [14]. Wireless communication between multiple users is one of the challenges for next-generation systems.

We consider a multi-user CRN with PU and SU pairs, as shown in Figure 2. Each SU transmitter and its corresponding SU receiver are within the transmission range of the other. Therefore, the existence of a communication between two SU depends on the time-varying activities of the PU. As illustrated in the figure, multiple SU can access the same channel, and one SU can have more than one channel for selection [15].

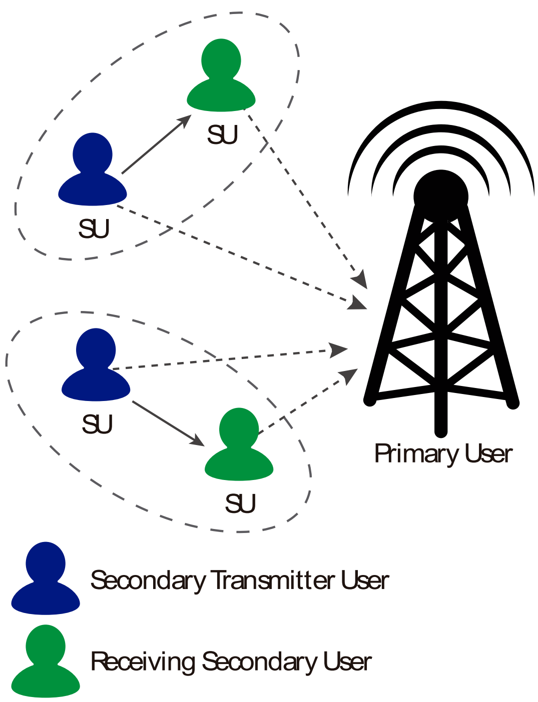

Figure 2: Multi-user scenario

Most studies assume that the usefulness of an SU is independent of the decisions made by other SU, however, such an assumption is not true, especially when considering scenarios in which SU share or compete for certain resources [16]. When making the channel access decision, each SU should not only consider the channel quality, but should also take into account the channel access decisions of other SU, the more the SU access the same channel, the lower the throughput. that can reach each SU due to interference between them [17], [18].

There are multiple spectral decision strategies to improve the performance of wireless networks [12], [19], [20], for distributed architectures the models that are generally implemented are Markov chains and game theory [20]–[22]. Numerous applications of Markov algorithms in CR have been employed for cognitive motor analysis [23]–[26].

This article implements and analyzes the decision-making process in CRN for multi-user access using Markov chains. To characterize the behavior of users in the radio environment, SU share information before accessing the spectrum. The analysis is performed for 3 SU access based on the number of total accumulated handoffs, number of total accumulated failed handoffs, average bandwidth, average delay, and average Throughput.

This work is organized in four sections. Section 2 presents a theoretical description of Markov chains. In section 3 the methodology is presented, which describes the structure of the proposed strategy with the respective algorithms used. The results obtained are presented in section 4. Section 5 presents the general conclusions of the work.

2. MARKOV CHAINS

A Markov chain or Markov model is a probability theory model that analyzes, through a finite number of states, the probability of an event occurring in a given time from the previous states. Markov chains can be represented as state diagrams (Figure 3). The states are equivalent to the nodes (circles) and the transition as lines with direction labeled with the respective probabilities [27]–[32].

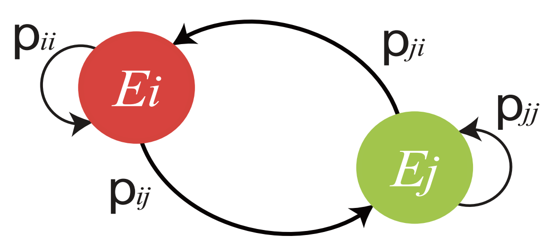

Figure 3: Representation of a Markov chain

In a finite chain with *m* possible states *E1, E2, ..., Em* the notation described through equation (1) is introduced.

Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

$$p_{ij} = P\left(X_n = j \mid X_{n-1} = i\right) \quad \forall i = 1, 2, \ldots, m \tag{1}$$

If $pij > 0$ the state Ei can communicate with Ej. Communication is mutual if $pji > 0$. For each fixed i, the values $\{pij\}$ are a probability distribution. The pij values are called transition probabilities and satisfy equatio (2).

$$\sum_{j=1}^{m} p_{ij} = 1 \quad where \quad p_{ij} > 0 \tag{2}$$

All the values are combined and form the transition matrix T of size $m \; x \; m$ (equation (3)). Where each row of the matrix is a probability distribution, that is, they satisfy equation (2).

$$T = [P_{ij}] = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \tag{3}$$

A particular analysis of a three-state Markov chain is presented in Figure 4. he transition matrix T of size $3 \; x \; 3$ is presented in equation (4).

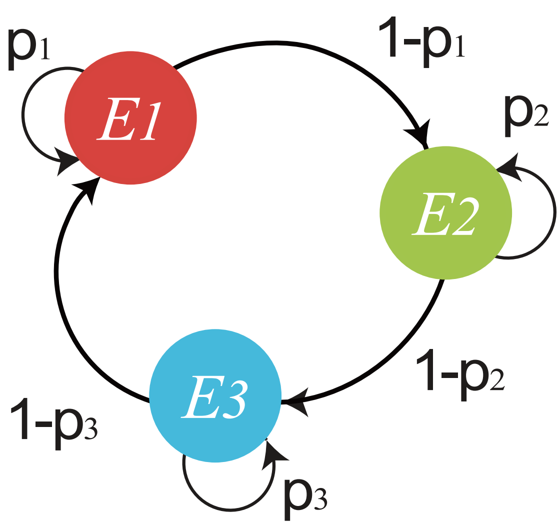

Figure 4: Three-state Markov chain

$$T = [P_{ij}]_{3x3} = \begin{pmatrix} p_1 & 1 - p_1 & 0 \\ 0 & p_2 & 1 - p_2 \\ 1 - p_3 & 0 & p_3 \end{pmatrix} \tag{4}$$

3. METHODOLOGY

This work analyzes the decision-making process in CRN with multi-user access. For decision making, Markov chains are implemented, spectral mobility metrics are used. Figure 5 presents the block diagram of the implemented strategy. The description of each of the blocks is described in detail in the following sections.

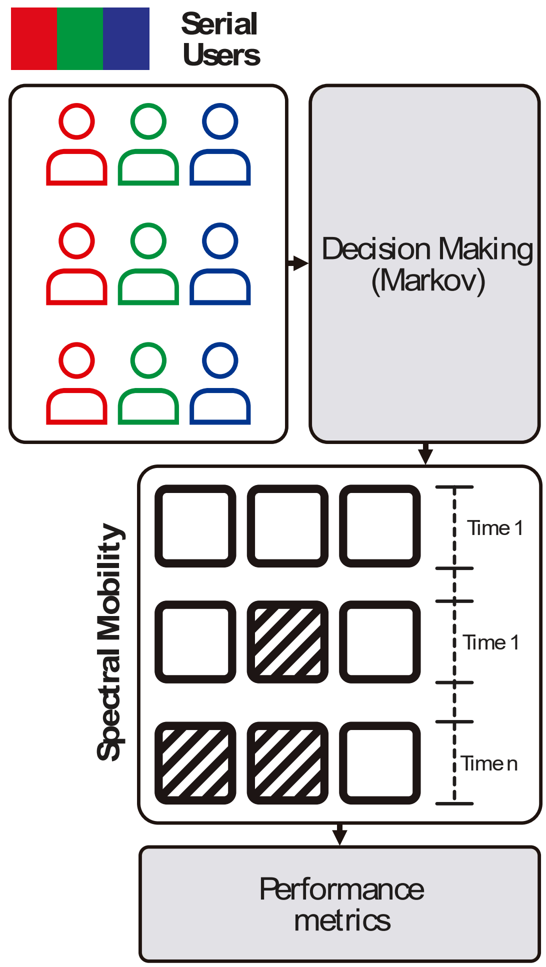

Figure 5: Block diagram implemented strategy

3.1. Multi-user Access (Serial Users)

Multi-user access on CRN is a challenge for next-generation networks. This work allows to include this characteristic, through the access of serial users in the decision-making process. The objective is to include the effect of SU decisions on the utility of the other SU. To include this behavior, an algorithm is developed that allows SU to share information before accessing the spectrum, and

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

according to this information, make access decisions to the respective channels.

The characteristics that can be assigned to the SU are diverse, this work analyzes the scenario where the different users present the same behavior. They all have the same priority and require the same resources. The methodology consists of serially sending a finite number of users, the number of users is a parameter that adjusts to the input of the model. Figure 6 presents the flow chart of the implemented multi-user access algorithm.

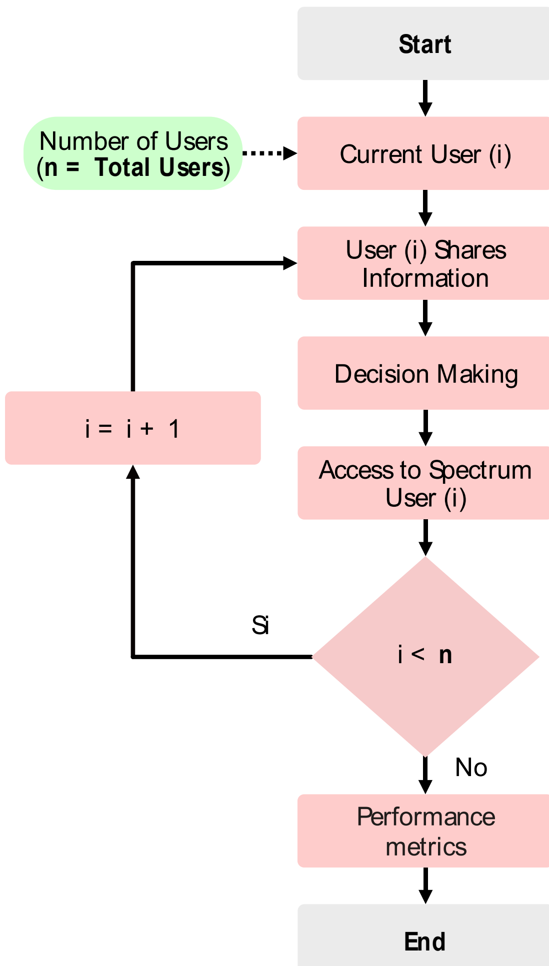

Figure 6: Multi-user access flowchart

3.2. Decision Making

The decision-making process is carried out by implementing Markov chains, the methodology consists of constructing the matrix of transition probabilities through the spectral occupation information. The spectral occupancy is an availability matrix measured through a monitoring system, this information characterizes the radio environment and allows training and evaluating the decision-making algorithm (Figure 6). The rows of the availability matrix represent the instants of time and the columns the channels. Table 1 presents the size of the data used for training and validation [33].

Table 1: Training and validation data

Data	Time Steps (Rows)	Channels (Columns)
Training	10800	550
Validation	1800	

The matrix of transition probabilities is obtained from the training data, establishes the probabilities of current and future state that are necessary for the implementation of the chains. The transition probabilities will be used in the validation of the model and will allow to quantify the spectral mobility. Markov chains establish as a requirement to know the current and future state of the system, this work defines a present state as the current time steps and the future state as the time *steps + 1*.

The strategy used for current states models each time steps as a positive integer. Figure 7 describes the methodology, each row of the training availability matrix is represented as a binary number, each bit corresponds to a channel. The available channels are represented as a logical one (1), the occupied channels are represented as a logical zero (0) [34], [35]. Subsequently, each of the binary representations of the channels is concatenated to form a single binary number for each time step, and the conversion from base 2 to base 10 is carried out.

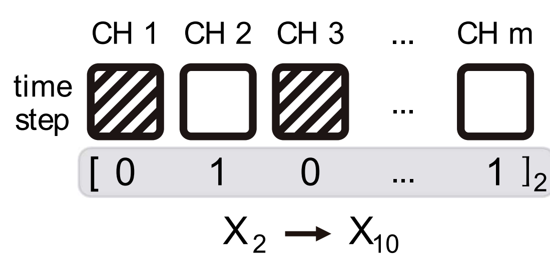

Figure 7: Representation of a current state

For future states, a sweep of the training matrix is performed according to the set of current states obtained, the states with the highest and lowest occurrence are determined by evaluating all the channels of the future time steps and finally the results are normalized. The flowchart in Figure 8 presents the logic of the algorithm implemented to establish current and future states. It starts with the representation of each time step as an integer, this decimal representation allows quantifying the current state and identifying the future state.

According to the number of future states identified, the prediction with the highest probability is determined. The general objective of the methodology is to establish a ranking for the channels, in the first positions of the ranking are the channels with the best availability probabilities, in the last positions of the ranking are the channels with the lowest availability probabilities. During spectral mobility, if an SU finds an available channel, it is said that the prediction was correct, if on the contrary, it finds that the channel is occupied by a PU, it is said that the prediction was low and must perform a channel jump according to the next best probability of availability established in the Ranking.

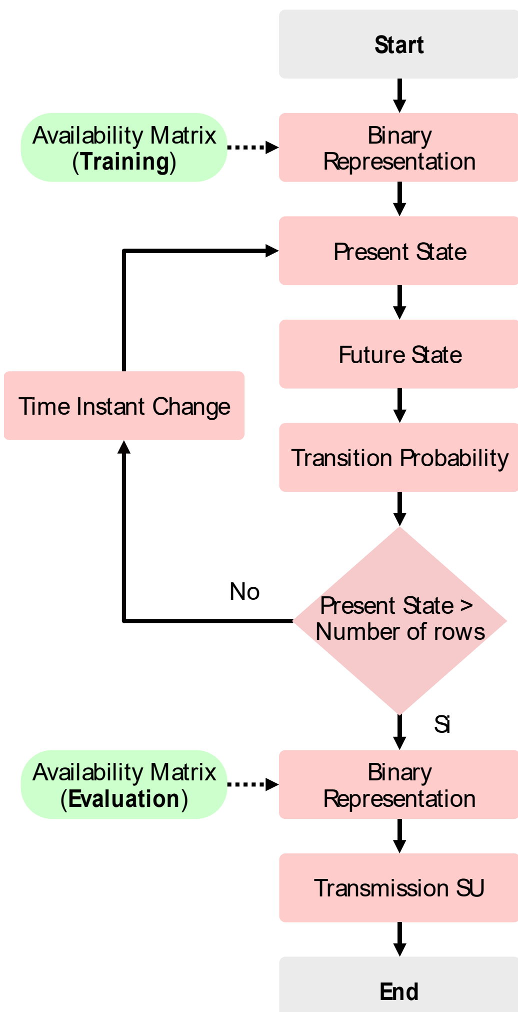

Figure 8: Decision-making flowchart with Markov

3.2.1. Spectral mobility

Spectral mobility is a function of the cognitive cycle that analyzes the channel changes or channel hopping that an SU performs. To quantify the spectral mobility of the multiple users, the behavior of the spectral handoffs is analyzed. Figure 9 presents the block diagram of the proposed model. For the evaluation of the model, the figures of bandwidth, handoffs, failed handoffs, delay and Throughput are used.

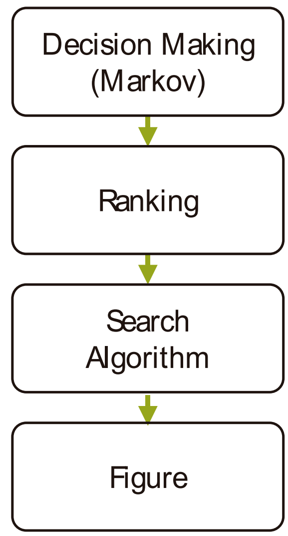

Figure 9: Spectral Mobility

Ranking for multiple user access: The Ranking is a row vector where the scores of the different channels are ordered in descending order. Scores are assigned according to the assigned probabilities in the present and future states. The highest scores represent the channels with the best odds, the lowest scores represent the channels with the lowest odds.

Multi-user search algorithm: This algorithm generates the spectral mobility information for multiple users. Use the previously generated Ranking as input information. According to the scores, it performs channel jumps (columns) in the availability matrix until it finds a spectral opportunity, when it finds an available channel, the algorithm makes a row change (time) and starts the search again, this process is repeated until the transmission time is complete. The process described corresponds to the analysis of spectral mobility of a user, for multiple users the analysis is equivalent, the difference is that the availability matrix is permanently updated indicating which channels have been occupied.

3.3. Performance Metrics

The metrics used correspond to the figures of the number of total accumulated handoffs, number of total accumulated failed handoffs, average bandwidth, average delay and the throughput average. Table 2 presents the description of the performance metrics for the decision-making technique used during the SU transmission time. For the number of users, there is no optimal configuration, it is a characteristic associated with the wireless network that needs to be analyzed. For this work, the access of 3 SU was analyzed during a transmission time of 9 minutes.

Table 2: Implemented performance metrics

Name	Description
Cumulative total handoff number	Number of handoffs performed
Cumulative number of failed handoffs	Number of handoffs that the SU could not materialize because it found the channel occupied
Average bandwidth	Average bandwidth used by the SU
Average delay	Total average time experienced by the SU during the transmission of a certain amount of information
Average Throughput	It is the effective data rate transmitted by the SU.

4. RESULTS

The results are presented through the metrics associated with performance. The algorithms were developed in MathWorks - Matlab R2020b, on a computer with 24 GB of RAM, an Intel (R) Core (TM) i7-7700HQ 2.8 GHz processor and a Microsoft Windows 10 64-bit operating system.

Figure 10 presents the behavior for the accumulated Handoff number, this metric is cost, therefore, the best performance is for the scenario with 1 SU access, the worst performance is for the scenario with 3 SU access.

Figure 11 presents the behavior for the accumulated number of Failed Handoffs, this metric is cost, therefore, the best performance is for the scenario with 1 SU access, the worst performance is for the scenario with 3 SU access.

Figure 12 presents the behavior for the Average Delay, this metric is cost and is obtained based on the number of handoffs, therefore, the best performance is for the scenario with 1 SU access, the worst performance is for the scenario with 3 SU access.

Figure 13 presents the Average Bandwidth, as it is a benefit metric, it is observed that during the 9 minutes of transmission the best performance is the scenario with 1 SU access presents the best performance, the worst performance is for the scenario with 3 SU access. For minute 2, 4 and 7 it is identified that the 2 SU scenario overlaps with the 1 SU.

Figure 14 presents the average throughput, as it is a benefit metric, it is observed that during, with the exception of minute 4, the scenario with 1 SU access presents the best performance, the worst performance is for the scenario with 3 SU access.

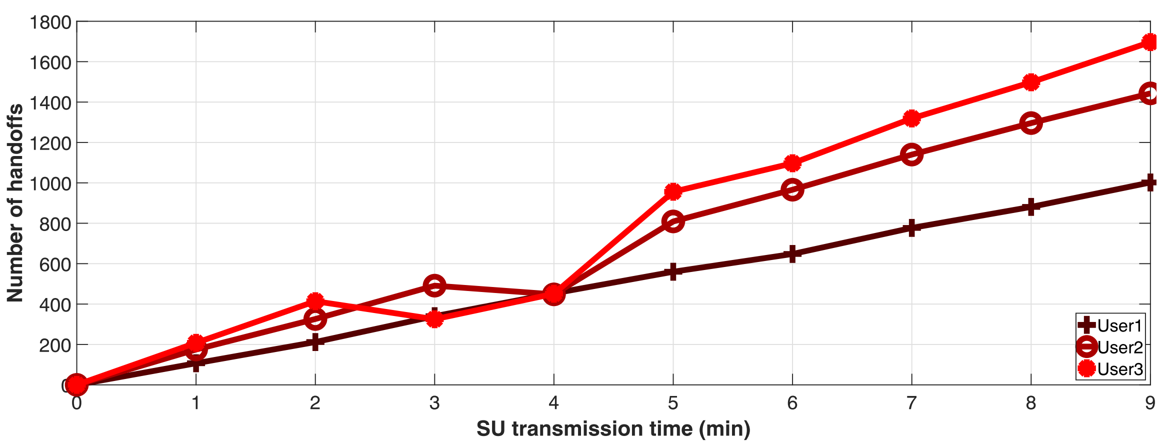

Figure 10: Cumulative number of Total Handoffs

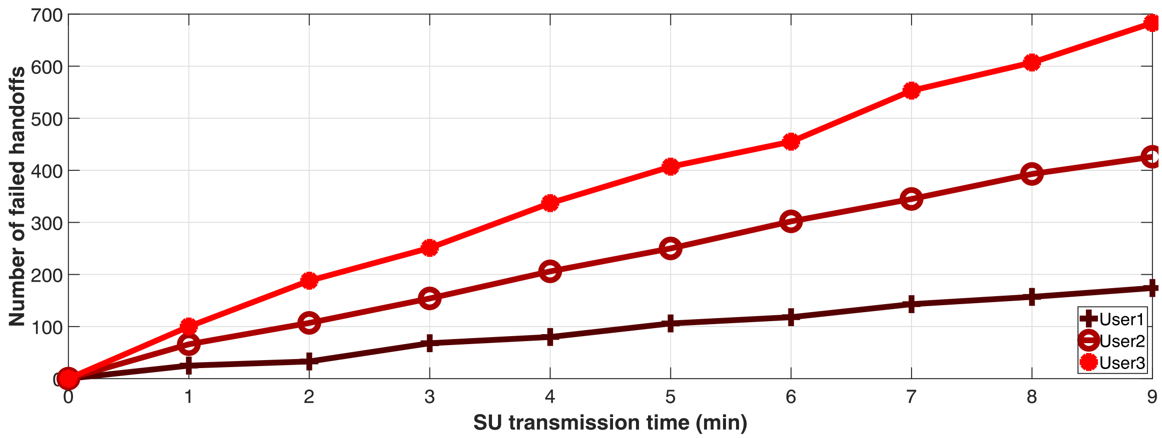

Figure 11: Cumulative number of Failed Handoffs

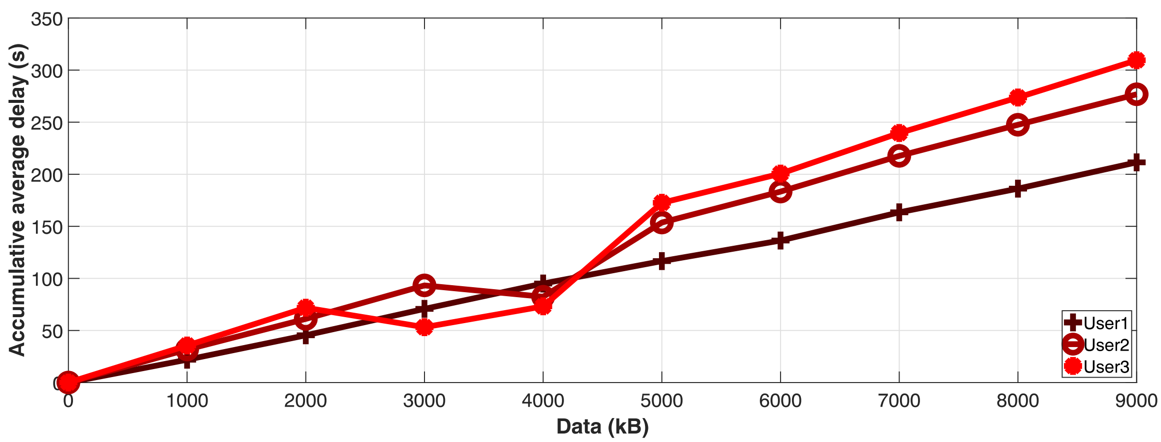

Figure 12: Average Delay

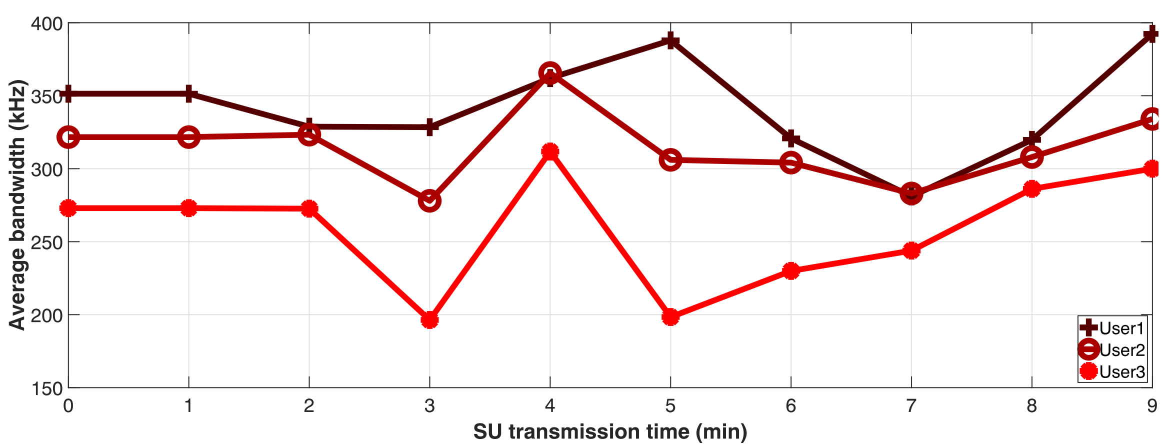

Figure 13: Average Bandwidth

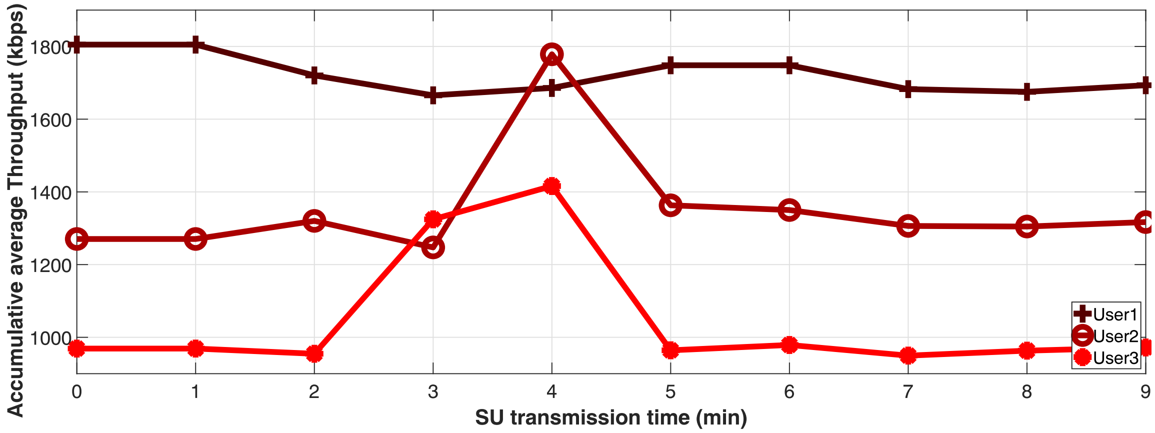

Figure 14: Average Throughput

Table 3 presents the results obtained for the accumulated cost metrics. In the case of the number of failed handoffs and the number of total handoffs are taken in the ninth minute of transmission of the SU, for the delay they correspond to the total average time during the transmission of 9000 kB. For the number of total handoffs, the increase as a function of the number of users presents a proportionality relationship of 1.44 and 1.69 for 2 SU and 3 SU respectively, assuming the access of 1 SU as the base scenario. For the number of failed handoffs, the increase as a function of the number of users presents a proportionality relationship of 2.45 and 3.93 for 2 SU and 3 SU respectively, assuming 1 SU access as the base scenario. For the average delay, the increase as a function of the number of users presents a proportionality relationship of 1.31 and 1.46 for 2 SU and 3 SU respectively, assuming access of 1 SU as the base scenario. Figure 15 presents the relationship for each user as a function of the 1 SU scenario.

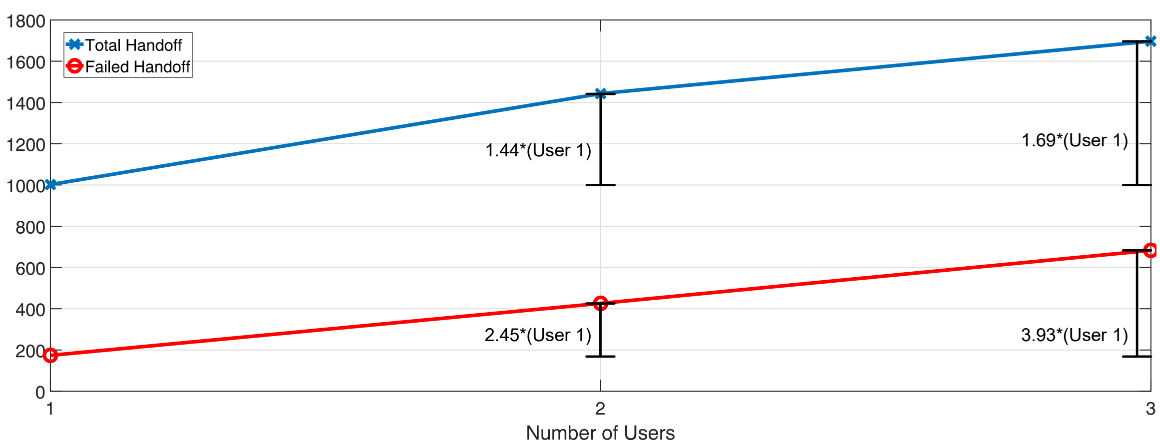

Figure 15: Behavior of cost metrics based on the 1 SU scenario

Table 3: Cumulative cost metrics

Users	Total Handoff	Failed Handoff	Average Delay
1 SU	1002	174	211.4
2 SU	1443	426	276.79
3 SU	1697	683	309.449

Journal of Theoretical and Applied Information Technology
30th November 2021. Vol.99. No 22

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Table 4 presents the results obtained for the accumulated profit metrics for the ninth minute of SU transmission. For the average bandwidth, the decrease as a function of the number of users presents a proportionality relationship of 0.85 and 0.76 for 2 SU and 3 SU respectively, assuming access of 1 SU as the base scenario. For the average Throughput, the decrease as a function of the number of users presents a proportionality relationship of 0.78 and 0.57 for 2 SU and 3 SU respectively, assuming access of 1 SU as a base scenario. Table 5 presents the relationship for each user as a function of the 1 SU scenario.

Table 4: Cumulative profit metrics

Users	Average Bandwidth (kHz)	Average Throughput (kbps)
1 SU	392.331	1693.36
2 SU	334.049	1316.99
3 SU	300	972.132

Table 5: Cumulative profit metrics

Users	Average Bandwidth (kHz)	Average Throughput (kbps)
1 SU	1	1
2 SU	0,85	0,78
3 SU	0,76	0,57

5. CONTRIBUTION, LIMITATIONS AND FUTURE WORK

The contributions and limitations of this article are described below, according to the results obtained and the comparative analysis with similar studies available in the literature, additional future work is presented, which was identified as a result of this study.

5.1. Contributions

The objective of this work was to implement and analyze the decision-making process in CRN for multi-user access using Markov chains. According to the results obtained, the contribution of this work was structured in four contributions:

- The exchange of information between SU before accessing the spectrum.
- Evaluation of a stochastic decision-making strategy under a spectral environment that allows multiple user access.
- Consideration of the real behavior of licensed users within the simulation environment.
- The performance metrics implemented, which, because they are associated with QoS characteristics, can be extended to any decision-making work in wireless networks.

According to the contributions previously described, and the literature review, two differences were identified with respect to the published research.

- The first difference is that no work was identified that would allow the analysis of decision-making and the access of multiple users to be included in the same scenario.
- The second difference is the performance metrics, the metrics implemented according to the analysis of the literature review, are exclusive to the proposed models, spectral mobility and QoS characteristics that can be easily adapted to other types of work are not studied.

5.2. Limitations

There are various characteristics and metrics that can be analyzed in the decision-making process for multi-user access, a description of the limitations and scope of this article is presented below.

- For the exchange of information, only what is shared is analyzed before accessing the spectrum.
- The information exchange scenarios are different, this work only analyzes the exchange between SU, the information that involves the PU is not evaluated.
- Bearing in mind that the exchange of information is only carried out between SU. This work only analyzes the effect of the decisions of the SU on the utility of the other SU.
- For the number of users, there is no optimal configuration, it is a characteristic associated with the wireless network that needs to be analyzed and the computing capabilities. For this work, the access of 3 SU was analyzed.
- The proposed methodology for the decision-making analysis will not contemplate propagation models, it is assumed that the distance between SU is close enough so that the fading does not affect the signal.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

5.3. Future Work

In CR, according to the literature review, the works are diverse and many questions remain to be answered. The final objective is to improve the use of the radioelectric spectrum and advances in software and hardware should be taken advantage of to solve more complex problems.

From an investigative approach, this work analyzed a stochastic model, however, other types of strategies can be implemented, for example artificial intelligence techniques, which have presented efficient results in decision-making. Additionally, to improve access to the network, security features must be included, therefore, it is necessary to analyze cryptography strategies.

From a social perspective, efficient use of the spectrum contributes to social and economic development, promoting the competitiveness of a region and improving the quality of life of the inhabitants. Therefore, future work consists of implementing the proposed strategy in real scenarios with real users.

6. CONCLUSION

RC is a broad field of research in the area of decision-making, according to each of the elements of the cognitive cycle there are various investigations and different techniques are found in the literature. The algorithms for the decision-making process must take advantage of the advances in probability to obtain efficient results, the work is permanent and requires integrating strategies with low computational load and with the ability to solve more complex problems.

This work analyzed the decision-making process in CRN for 3 SU access based on the number of total accumulated handoffs, number of total accumulated failed handoffs, average bandwidth, average delay and average Throughput. According to the analysis of results, the best performance is for the scenario with access of 1 SU and the worst performance is for the scenario with access of 3 SU. Regarding the general analysis of the cost metrics, an increase was identified as a function of the number of users with a proportionality relationship in the range of 1 - 3 times, assuming the access of 1 SU as a baseline scenario. Regarding the general analysis of the benefit metrics, a reduction was identified as a function of the number of users with a proportionality relationship in the range of 0.5 - 0.95 times, assuming access of 1 SU as a baseline scenario.

REFERENCES

[1] CISCO, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update," *CISCO*. 2021, Accessed: Jan. 29, 2019. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html.

[2] M. Tahir, M. Hadi Habaebi, and M. R. Islam, "Novel distributed algorithm for coalition formation for enhanced spectrum sensing in cognitive radio networks," *AEU - Int. J. Electron. Commun.*, vol. 77, no. Supplement C, pp. 139–148, 2017, doi: https://doi.org/10.1016/j.aeue.2017.04.033.

[3] K. Kumar, A. Prakash, and R. Tripathi, "Spectrum handoff in cognitive radio networks: A classification and comprehensive survey," *J. Netw. Comput. Appl.*, vol. 61, no. Supplement C, pp. 161–188, 2016, doi: https://doi.org/10.1016/j.jnca.2015.10.008.

[4] C. Hernandez, H. Marquez, and D. Giral, "Comparative Evaluation of Prediction Models for Forecasting Spectral Opportunities," *IJET*, vol. 9, no. 5, pp. 3775–3782, Oct. 2017, doi: 10.21817/ijet/2017/v9i5/170905055.

[5] C. Hernández, L. Pedraza, I. Páez, and E. Rodríguez-Colina, "Análisis de la Movilidad Espectral en Redes de Radio Cognitiva," *Inf. tecnológica*, vol. 26, no. 6, pp. 169–186, 2015.

[6] S. Cruz-Pol, L. Van Zee, N. Kassim, W. Blackwell, D. Le Vine, and A. Scott, "Spectrum Management and the Impact of RFI on Science Sensors," in *Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment (MicroRad)*, 2018, pp. 1–5, doi: 10.1109/MICRORAD.2018.8430720.

[7] I. F. Akyildiz, Won-Yeol Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, Apr. 2008, doi: 10.1109/MCOM.2008.4481339.

[8] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Comput. Networks*, vol. 50, no. 13, pp. 2127–2159, Sep. 2006, doi:

10.1016/j.comnet.2006.05.001.
[9] N. Abbas, Y. Nasser, and K. El Ahmad, "Recent advances on artificial intelligence and learning techniques in cognitive radio networks," *EURASIP J. Wirel. Commun. Netw.*, vol. 1, no. 2015, p. 174, Dec. 2015, doi: 10.1186/s13638-015-0381-7.
[10] R. Joda and M. Zorzi, "Decentralized Heuristic Access Policy Design for Two Cognitive Secondary Users under a Primary Type-I HARQ Process," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4037–4049, 2015, doi: 10.1109/TCOMM.2015.2480846.
[11] Y. Rizk, M. Awad, and E. W. Tunstel, "Decision Making in Multi-Agent Systems: A Survey," *IEEE Trans. Cogn. Dev. Syst.*, vol. 10, no. 3, pp. 1–15, 2018, doi: 10.1109/TCDS.2018.2840971.
[12] F. Hu, B. Chen, X. Zhai, and C. Zhu, "Channel Selection Policy in Multi-SU and Multi-PU Cognitive Radio Networks with Energy Harvesting for Internet of Everything," *Mob. Inf. Syst.*, vol. 2016, p. 6024928, 2016, doi: 10.1155/2016/6024928.
[13] M. T. Masonta, M. Mzyece, and N. Ntlatlapa, "Spectrum Decision in Cognitive Radio Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 15, no. 3, pp. 1088–1107, 2013, doi: 10.1109/SURV.2012.111412.00160.
[14] B. Zhang, Y. Chen, C. Wang, and K. J. R. Liu, "Learning and decision making with negative externality for opportunistic spectrum access," in *2012 IEEE Global Communications Conference (GLOBECOM)*, 2012, pp. 1404–1409, doi: 10.1109/GLOCOM.2012.6503310.
[15] C. Jiang, Y. Chen, and K. J. R. Liu, "Sequential multi-channel access game in distributed cognitive radio networks," in *2014 IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, 2014, pp. 1247–1251, doi: 10.1109/GlobalSIP.2014.7032322.
[16] K.-T. Feng, P.-R. Li, S.-K. Hsu, J.-S. Lin, and T.-S. Chang, "Novel Design on Multiple Channel Sensing for Partially Observable Cognitive Radio Networks," *IEEE Trans. Mob. Comput.*, vol. 16, no. 8, pp. 2260–2275, 2017, doi: 10.1109/TMC.2016.2615925.
[17] Y. C. Cheng, E. H. Wu, and G. H. Chen, "A Decentralized MAC Protocol for Unfairness Problems in Coexistent Heterogeneous Cognitive Radio Networks Scenarios With Collision-Based Primary Users," *IEEE Syst. J.*, vol. 10, no. 1, pp. 346–357, 2016, doi: 10.1109/JSYST.2015.2431715.
[18] M. R. Ramzan, N. Nawaz, A. Ahmed, M. Naeem, M. Iqbal, and A. Anpalagan, "Multi-objective optimization for spectrum sharing in cognitive radio networks: A review," *Pervasive Mob. Comput.*, vol. 41, pp. 106–131, 2017, doi: 10.1016/j.pmcj.2017.07.010.
[19] N. Armi, M. Z. Yusoff, and N. M. Saad, "Cooperative spectrum sensing in decentralized cognitive radio system," in *Eurocon 2013*, 2013, pp. 113–118, doi: 10.1109/EUROCON.2013.6624974.
[20] C. Gao, Z. Fang, J. Lin, X. Guan, and J. He, "Model averaging and probability of detection estimation under hierarchical uncertainties for Lamb wave detection," *Mech. Syst. Signal Process.*, vol. 165, p. 108302, 2022, doi: https://doi.org/10.1016/j.ymssp.2021.108302.
[21] R. Ghosal and S. K. Ghosh, "Bayesian inference for generalized linear model with linear inequality constraints," *Comput. Stat. Data Anal.*, vol. 166, p. 107335, 2022, doi: https://doi.org/10.1016/j.csda.2021.107335.
[22] K. Cheng, Z. Lu, S. Xiao, and J. Lei, "Estimation of small failure probability using generalized subset simulation," *Mech. Syst. Signal Process.*, vol. 163, p. 108114, 2022, doi: https://doi.org/10.1016/j.ymssp.2021.108114.
[23] P. Ni, Q. Han, X. Du, and X. Cheng, "Bayesian model updating of civil structures with likelihood-free inference approach and response reconstruction technique," *Mech. Syst. Signal Process.*, vol. 164, p. 108204, 2022, doi: https://doi.org/10.1016/j.ymssp.2021.108204.
[24] S. Khan, P. Saengudomlert, and A. Taparugssanagorn, "Modeling and delay performance analysis of wireless regional area networks under incumbent coexistence and self-coexistence with multichannel operations," *Int. J. Commun. Syst.*, vol. 34, no. 3, p. e4681, Feb. 2021, doi: https://doi.org/10.1002/dac.4681.
[25] S. A. Attalla, K. G. Seddik, A. A. El-Sherif, and T. ElBatt, "A Reinforcement Learning Approach to ARQ Feedback-based Multiple Access for Cognitive Radio Networks," in *2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC)*, 2021, pp. 1–5, doi: 10.1109/CCNC49032.2021.9369562.
[26] Q. Xu, S. Li, T. V Do, K. Jia, and N. Yang, "Performance Analysis of Cognitive Radio Networks With Burst Dynamics," *IEEE Access*, vol. 9, pp. 110627–110638, 2021, doi:

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

10.1109/ACCESS.2021.3103321.
[27] I. S. Abdelfattah, S. I. Rabia, and A. M. Abdelrazek, “Optimal sensing energy and sensing interval in cognitive radio networks with energy harvesting,” *Int. J. Commun. Syst.*, vol. 34, no. 7, p. e4742, May 2021, doi: https://doi.org/10.1002/dac.4742.
[28] J. Tiwari, A. Prakash, and R. Tripathi, “A novel cooperative MAC protocol for safety applications in cognitive radio enabled vehicular ad-hoc networks,” *Veh. Commun.*, vol. 29, p. 100336, 2021, doi: https://doi.org/10.1016/j.vehcom.2021.10033.
[29] A. Taggu and N. Marchang, “Detecting Byzantine attacks in Cognitive Radio Networks : A two-layered approach using Hidden Markov Model and machine learning,” *Pervasive Mob. Comput.*, vol. 77, p. 101461, 2021, doi: https://doi.org/10.1016/j.pmcj.2021.101461.
[30] C. Hernández and D. Giral, “Spectrum Mobility Analytical Tool for Cognitive Wireless Networks,” *Int. J. Appl. Eng. Res.*, vol. 10, no. 21, pp. 42265–42274, 2015.
[31] L. F. Pedraza, F. Forero, and I. Paez, “Evaluación de ocupación del espectro radioeléctrico en Bogotá-Colombia,” *Ing. y Cienc.*, vol. 10, no. 19, pp. 127–143, 2014.
[32] L. F. Pedraza, C. Hernández, K. Galeano, E. Rodríguez-Colina, and I. Páez, *Ocupación espectral y modelo de radio cognitiva para Bogotá*, Primera. Bogotá: Universidad Distrital Francisco José de Caldas, 2016.