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HYBRID ALLOCATION MODEL TVWS IN BOGOTA CITY

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Abstract

The digital migration of television offers an opportunity to improve the spectral efficiency through TV White Spaces, which are frequencies allocated within the television bands that are not under use over certain time periods and in specific geographical locations. The present article proposes a hybrid spectrum allocation model between FAHP and TOPSIS for the efficient use of the digital television band in the city of Bogotá based on cognitive radio. The proposed methodology is derived from the results of a metering campaign previously carried out in the digital TV band that is currently implemented in Bogotá, Colombia. After organizing and statistically analysing spectral information, it is proposed to develop a hybrid model for the allocation of TV White Spaces, based on FAHP and TOPSIS algorithms. The results show a good performance of the proposed model in the spectrum allocation phase in digital TV bands. The obtained performance is 9% to 15% below the ideal solution and reaches average throughput rates of 4 Mbps and a bandwidth of 820 kbps.

Keywords: Cognitive radio, Digital television, Frequency band, Spectrum allocation, Spectral opportunity , White spaces.

1. Introduction

Currently, the electromagnetic spectrum is presented as a scarce resource due to the exponential increase in the usage of mobile devices, access to wireless internet, IoT applications, smart grids, as well as other technologies that require said resource for communications [1,2]. However, previous studies have proven that the electromagnetic spectrum is used inefficiently since there are time-space periods in which the resource is not being occupied. Hence, it could be harnessed by secondary users that need the service [3-6] thus prompting the efficient use of the spectrum.

In this scenario, cognitive radio could be considered an adequate solution since it allows the autonomous detection of the available spectrum known as spectral opportunities (SO). Through the prediction of the behaviour of primary users (PU) in the network, said SO could be used and the operation parameters could be reset in order to adapt to changes [7-9].

On another note, moving from analog to digital television results in the release of a considerable amount of bandwidth in the radioelectric spectrum, within the VHF/UHF bands in which these signals operate, due to the efficiency that characterizes digital television. This new spectrum is known as the ‘digital dividend’ which in most countries is auctioned for new services [10]. However, in the digital television band, additional spectral opportunities known as TV White Spaces (TVWS) arise in which an absence of the TV signal carrier is detected and that could be harnessed by cognitive radio systems [9, 11-17].

Given the previous scenario, this article proposes a hybrid spectrum allocation model that combines the Fuzzy Analytical Hierarchy Process (FAHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the efficient use of the digital television band in the city of Bogotá through cognitive radio. The FAHP algorithm is in charge of determining the importance weight of each parameter or decision-related criterion that has been chosen. Weights are assigned a value below the unit and their sum is equal to the unit. This information is communicated to the TOPSIS algorithm, which carries out calculations for the assessment of alternatives based on the distances to the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). Thus, the ideal solution is determined which enables the selection of the required spectral opportunity. The novelty of this model lies in the combination of two algorithms, the inclusion of fuzzy logic to handle information with uncertainties and the feedback between both algorithms to achieve better results.

Furthermore, the behaviour of the algorithms was analysed in terms of four criteria:

1) The probability of channel availability (PD).
2) The estimated channel time availability (TED).
3) The signal to interference plus noise ratio (PSINR).
4) The bandwidth (BW).

On another note, the assessment of the hybrid algorithm was based on five performance metrics:

1) Accumulative Average of Performed Handoffs (AAPH).
2) Accumulative Average of Failed Handoffs (AAFH).
3) Accumulative Average of the Transmission Delay (AATD).
4) Average of Transmission Bandwidth (ATB).Accumulative Average of Transmission Throughput (AATT).

2. Experimental Procedure

Initially, spectral occupancy is characterized and the possible TVWS are identified in the band to be used in cognitive radio. Afterwards, it is proposed to use the FAHP algorithm combined with the TOPSIS algorithm to generate a hybrid model of spectrum allocation that allows harnessing TVWS present in the digital TV band.

The present work uses the spectrum information gathered in a metering campaign carried out in 2012 and updated in 2019 in different points of the city of Bogotá for two months. The campaign took into account the frequency range allocated to the digital TV service in Bogotá, which stands between 470 and 560 MHz. Nonetheless, not all channels within this range are being used. Table 1 shows the allocation of channels according to the city-based operator.

Table 1. Spectrum allocation for the digital TV band in Bogotá.

TV Operator	Channel (MHz)	Central Frequency (MHz)
Caracol	470 - 476	473
RCN	476 - 482	479
RTVC	482 - 488	485
Government	488 - 494	491
City TV	548 - 554	551
Canal Capital	554 - 560	557

A set of measurements was initially carried out in the frequency range between 400 and 600 MHz distributed in four intervals of 50 MHz each (400 - 450. 450 - 500, 500 - 550, 600 - 650 MHz). For each interval, a total of 551 frequency channels were measured so that each channel corresponds to a segment of close to 100 kHz (50 MHz / 551). The measurements were taken with a spectrum analyser and an omnidirectional antenna in the Engineering School of Univerisdad Distrital Francisco José de Caldas.

2.1. Hybrid Spectrum Allocation Model FAHP-TOPSIS

The proposed spectrum allocation model is a hybrid between FAHP and TOPSIS algorithms as described in Fig. 1. The metering campaign offers information on the spectrum, which is then organized and stored in the database. Said information is used to perform the statistical calculations needed to determine the values of each decision parameter. The previous information is delivered to the FAHP and TOPSIS algorithms. The FAHP algorithm is in charge of determining the weight of each parameter or decision-related criterion that has been selected. Said weights are assigned a value below the unit and their sum is equal to the unit. This information is communicated to the TOPSIS algorithm which then assesses the alternatives based on the distances to the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). Hence, the ideal solution is stated and the required spectral opportunity is selected. The information on spectrum opportunity is handed to the FAHP algorithm so it can factor it into the next calculation.

FAHP and TOPSIS are decision-making multi-criteria algorithms that have shown good results in different types of applications. This, in addition to the inclusion of fuzzy logic with the FAHP method, can operate information with uncertainty while TOPSIS guarantees proper results at a fairly low computational cost. It can be concluded that the combination of both strategies can deliver satisfying results.

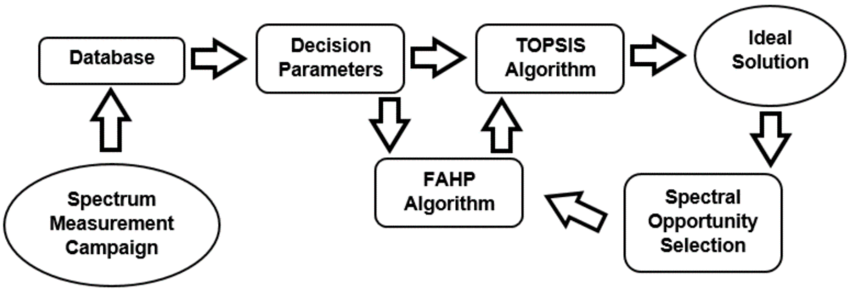

Fig. 1. Proposed spectrum allocation model.

2.2. FAHP algorithm

The FAHP algorithm has been studied in [18] and applied in the GSM (Global System for Mobile Communications) bands leading to satisfying results.

The calculation of the weights for each criterion is based on Eqs. (1) to (9).

$$\widetilde{S_i} = \sum_{j=1}^{n} \widetilde{a_{ij}} \left[\sum_{i=1}^{n} \sum_{j=1}^{n} \widetilde{a_{ij}}\right]^{-1} \tag{1}$$

where:

$$\sum_{j=1}^{n} \widetilde{a_{ij}} \; \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij}\right) \tag{2}$$

And the reverse matrix is obtained as:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{n} \widetilde{a_{ij}}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} u_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}}, \times \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} l_{ij}}\right) \tag{3}$$

The ‘degree of possibility’ for the fuzzy convex number to be larger than k convex, the fuzzy number are given from Eqs. (4) and (5).

$$V\left(\tilde{S} \geq \widetilde{S_i}\right) = V\left[\left(\tilde{S} \geq \widetilde{S_1}\right) \wedge \left(\tilde{S} \geq \widetilde{S_2}\right) \wedge \cdots \left(\tilde{S} \geq \widetilde{S_k}\right)\right] \tag{4}$$

$$V\left(\tilde{S} \geq \widetilde{S_i}\right) = \left\{V\left(\tilde{S} \geq \widetilde{S_i}\right)\right\} \tag{5}$$

where the degree of possibility that $V\left(\tilde{S}_1 \geq \widetilde{S_2}\right)$ y $V\left(\tilde{S}_2 \geq \widetilde{S_1}\right)$ is given by Eqs. (6) and (7).

$$V\left(\tilde{S}_1 \geq \widetilde{S_2}\right) = \begin{cases} 1, m_1 \geq m_2 \\ 0, l_2 \geq u_1 \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)}, opposite\ case \end{cases} \tag{6}$$

$$V\left(\tilde{S}_2 \geq \widetilde{S_1}\right) = \begin{cases} 1, m_2 \geq m_1 \\ 0, l_1 \geq u_2 \\ \frac{l_2 - u_1}{(m_2 - u_2) - (m_1 - l_1)}, opposite\ case \end{cases} \tag{7}$$

Now, assuming that $d'_1 = min\left\{V\left(\tilde{S}_1 \geq \widetilde{S_2}\right)\right\}$, the vector weight is given by Eq.(8).

$$w' = (d'_1, d'_2, \ldots, d'_n) \tag{8}$$

Finally, after normalization, the non-diffuse weight vector is given by Eq. (9).

$$W = (d_1, d_2, \dots, d_n)^T = \left(\frac{d'_1}{\sum_{i=1}^{n} d'_i}, \frac{d'_2}{\sum_{i=1}^{n} d'_i}, \dots, \frac{d'_n}{\sum_{i=1}^{n} d'_i}\right) \tag{9}$$

2.3. TOPSIS algorithm

TOPSIS (*Technique for Order Preferences by Similarity to Ideal Solution*) is a method used to solve decision-making problems that involve multiple options. The basic concept is the assessment of alternatives based on the distances to the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). PIS is the most preferred alternative by the decision maker (DM) since it maximizes benefit and minimizes cost, while the NIS is least preferred solution since it minimizes benefit and maximizes cost [19, 20]. Thus, the preferred solution is the one closest to the ideal solution (PIS) and the farthest from the discarded solution (NIS). The metric is obtained for the Euclidian distance between the criterion and the weights. The steps required for this purpose are the following [19].

1) Normalize the decision matrix X through the square root normalization method. Build the decision matrix with standard weights X, as shown in Eq. (10).

$$\check{X} = \begin{bmatrix} \check{X}_{11} & \cdots & \check{X}_{1M} \\ \vdots & \ddots & \vdots \\ \check{X}_{N1} & \cdots & \check{X}_{NM} \end{bmatrix} = \begin{bmatrix} \omega_1 \tilde{x}_{11} & \cdots & \omega_M \tilde{x}_{1M} \\ \vdots & \ddots & \vdots \\ \omega_1 \tilde{x}_{N1} & \cdots & \omega_M \tilde{x}_{NM} \end{bmatrix} \tag{10}$$

where ω_i is the weight given to criterion i.

2) The positive (PIS) and negative (NIS) ideal solutions are given by Eqs. (11) and (12).

$$A^+ = \{(max\, \tilde{x}_{ij} \mid j \in X^+), (min\, \tilde{x}_{ij} \mid j \in X^-)\} = \{\tilde{x}_1^+, \dots, \tilde{x}_M^+\} \tag{11}$$

$$A^- = \{(min\, \tilde{x}_{ij} \mid j \in X^+), (max\, \tilde{x}_{ij} \mid j \in X^-)\} = \{\tilde{x}_1^-, \dots, \tilde{x}_M^-\} \tag{12}$$

where $i = 1, \dots N$ y X^+ y X^- are the sets of benefits and costs, respectively.

3) For each alternative, the Euclidian distance D is computed with Eqs. (13) and (14).

$$D_i^+ = \sqrt{\sum_{j=1}^{M} (\tilde{x}_{ij} - \tilde{x}_j^+)^2} \qquad i = 1, \dots, N \tag{13}$$

$$D_i^- = \sqrt{\sum_{j=1}^{M} (\tilde{x}_{ij} - \tilde{x}_j^-)^2} \qquad i = 1, \dots, N \tag{14}$$

4) Finally, the alternatives are organized in descending order according to the preference index given by Eq. (15).

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-} \qquad i = 1, \dots, N \tag{15}$$

2.4. Assessment methodology

The obtained spectrum occupancy data and the processing stage in the analysis section are used to perform a set of simulations using the ‘Cognitive Radio Networks’ tool for the analysis of the spectral mobility described in [21]. The hybrid FAHP-TOPSIS algorithm can be adjusted as a method for dynamic spectrum allocation in a cognitive radio network, based on the data of the behaviour of PUs in the digital TV band.

The simulation tool allocates channels or frequencies based on four criteria:

1) The probability of channel availability (PD).
2) The estimated channel time availability (TED).
3) The signal to interference plus noise ratio (PSINR),
4) The bandwidth (BW).

On another note, the assessment of the hybrid algorithm was based on five performance metrics:

1) Accumulative Average of Performed Handoffs (AAPH).
2) Accumulative Average of Failed Handoffs (AAFH).
3) Accumulative Average of the Transmission Delay (AATD).
4) Average of Transmission Bandwidth (ATB).

These four parameters are sub-criteria that were chosen for the FAHP algorithm previously discussed. The calculation of said criteria is carried out for the simulation tool based on the inputted spectral occupancy data.

The assessment of the hybrid algorithm is carried out based with five performance metrics:

1) Accumulative Average of Performed Handoffs (AAPH).
2) Accumulative Average of Failed Handoffs (AAFH).
3) Accumulative Average of the Transmission Delay (AATD).
4) Average of Transmission Bandwidth (ATB).
5) Accumulative Average of Transmission Throughput (AATT) [21].

Finally, the results of the FAHP-TOPSIS model are compared to those obtained with a simple random selection model of spectral opportunities based on the occupancy data measured in the TV bands, adjusted in the simulation tool, as a base for both models.

3. Results and Discussion

The results obtained are described in Figs. 2 to 6, where three different allocation models are presented:

1) The proposed ‘average’ model which corresponds to the results obtained through several simulations using the hybrid model.
2) The proposed ‘perfect’ model that corresponds to the results of the ideal allocation model for the parameters established in the simulator; and
3) The ‘random’ model that corresponds to a simple algorithm that allocates channels randomly without considering any paradigm.

3.1. Number of total handoffs

The total number of handoffs represents the total number of changes of channel that the algorithm had to make in the transmission period of 10 minutes, maintaining the matrix of available spectral opportunities as the basis. In Fig. 2, the spectral number of handoffs is plotted for each allocation model.

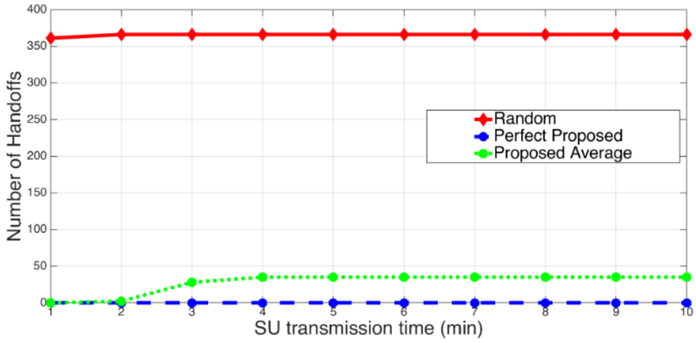

Fig. 2. Total number of handoffs performed during SU transmission.

In this chart, the total number of handoffs is always null (‘0’) for the ‘perfect’ method since it represents the ideal model as previously mentioned and, hence, frequency changes should not take place during transmission given that the best channel available is chosen. Meanwhile, the proposed ‘average’ method presents a gradual increase until minute 4 where 40 handoffs or spectral movements have already occurred and this is consistent until the transmission is concluded. Furthermore, the simple random allocation algorithm performs unfavourably as the number of handoffs is high throughout the 10-minute transmission with a value close to 360 in average for each time instant.

3.2. Number of failed handoffs

The number of failed handoffs corresponds to the events in which the channel chosen by the algorithm was requested unsuccessfully given that the channel was already occupied by a PU during the transmission period. Figure 3 shows the results plotted for each model.

In this chart, as in the previous one, the number of failed handoffs of the ‘perfect’ method is always ‘0’ since it can choose the channel to be used throughout the transmission period without suffering from handoffs. On another note, the results of the ‘average’ algorithm show that the number of failed handoffs increases progressively between minutes 2 and 4 and then a constant value of 10 is maintained until transmission is concluded. Ultimately, the random allocation model delivers a high number of failed handoffs with a value of 180 throughout the transmission period, which makes it a fairly weak method.

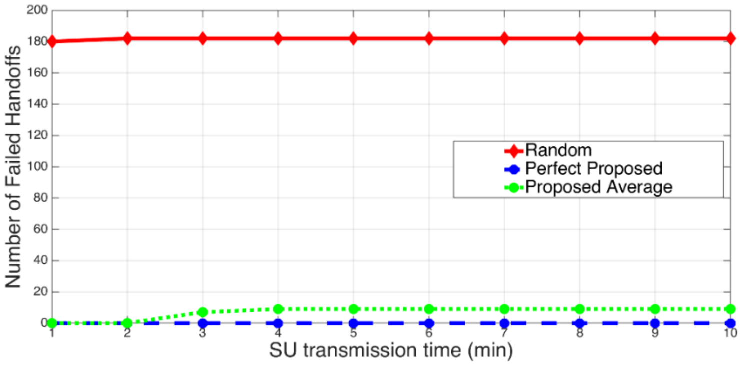

Fig. 3. Number of failed handoffs performed during SU transmission.

3.3. Bandwidth

It corresponds to the average available bandwidth during transmission. The simulator has the possibility to take up to four adjacent channels to the right and four adjacent channels to the left, that are available so that bandwidth is increase and spectral opportunities are efficiently harnessed. Figure 4 presents the results from simulations for each model.

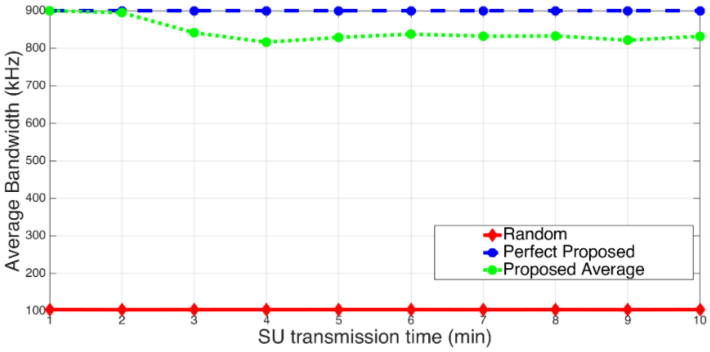

Fig. 4. Bandwidth available during SU transmission.

As seen in the previous chart, the resulting bandwidth for the 'perfect' algorithm holds a constant value of 900 kHz which is the maximum bandwidth available corresponding to four channels to the right and four channels to the left for a total of 9 channels including the central channel. Each channel has a bandwidth of 100 kHz. The 'average' algorithm presents an acceptable behaviour in terms of bandwidth availability, given that it reaches 900 kHz within the first minute and maintains a progressive variation with an average over 800 kHz from minute 2. Lastly, the results of the random algorithm are unfavourable in terms of bandwidth since the variable stands at 100 kHz (minimum) during the entire transmission time. This means that only one channel is taken which makes it a poorly efficient method spectrum-wise.

3.4. Average accumulative delay

The average accumulative delay shows that time taken by the algorithm to transmit a specific amount of data. The delay is directly related to the number of handoffs taking place during transmission. A higher number of handoffs implies an increase in the delay during transmission. Figure 5 shows the results obtained for each model.

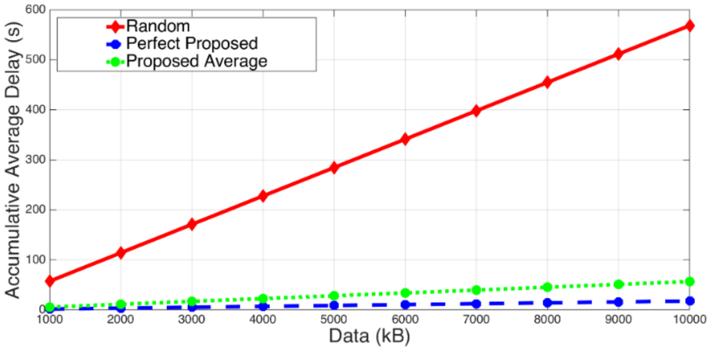

Fig. 5. Average accumulative delay vs number of transmitted data.

The previous chart shows that the average delay is always lower for the 'perfect proposed' algorithm as expected since it delivers zero handoffs during transmission. The only time considered is the processing time of the algorithm, which would correspond in a real application to the transmission delay due to the medium. In terms of the results of the 'proposed perfect' algorithm, the average accumulative delay is slightly higher than in the ideal model although remaining below 100 seconds throughout the transmission time. This is explained by the fact that there are handoffs during transmission. The system takes about 60 seconds to transmit 10 MB. Lastly, the random algorithm presents the worst performance since the number of handoffs during transmission is high which increases the average accumulative delay whose maximum value is close to the 600 seconds required to transmit 10 MB of data.

3.5. Throughput

Throughput represents the average flow of information that can be transmitted during the 10-minute transmission period. Figure 6 presents the results for each model.

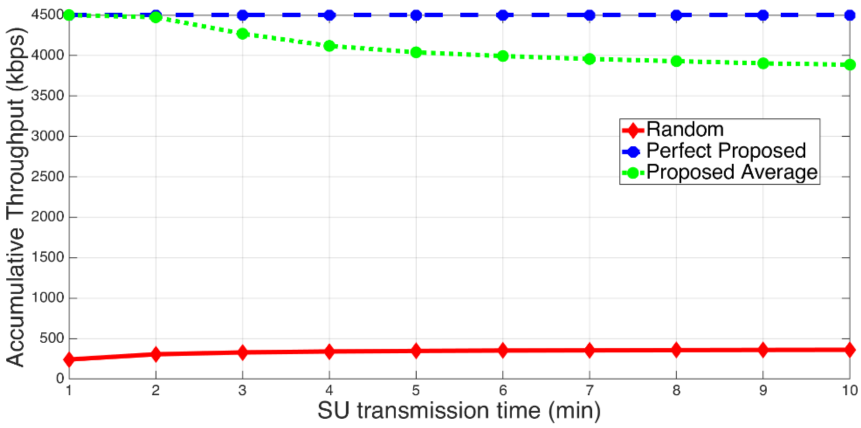

Fig. 6. Average throughput available during SU transmission.

Throughput is defined as the maximum capacity of data transmission, in terms of bandwidth based on the Shannon-Hartley theorem, expressed in Eq. (16).

$$C = B \cdot log_2\left(1 + \frac{S}{N}\right) \quad (16)$$

where C corresponds to the channel capacity (measured in bps), B is the electric bandwidth (measured in Hz) and S/N corresponds to the signal-to-noise ratio present in the transmission environment.

If the signal-to-noise ratio is equal to 31 based on Eq. (16) and the channel bandwidth is 100 kHz, then the total channel capacity is 500 Kbps. Hence, the 'perfect' proposed method maintains a constant throughput of 4500 Kbps in the entire simulation time. This corresponds to the sum of maximum available bandwidth comprised of 9 channels based on the simulator parameters.

Furthermore, throughput reaches 4500 Kbps over the first minute for the 'average' proposed case which would indicate the complete availability of all 9 channels. After minute 2, throughput is reduced progressively as a result of the required handoffs until it reaches a minimum value of 4000 Kbps at the end of transmission. The results of the random algorithm are fairly deficient in terms of throughput, which remains below 500 Kbps as a result of the high number of handoffs required for transmission and the wrongful choice of transmission channel. This has a direct impact on bandwidth availability since it remains at a maximum of 100 kHz during the transmission period as previously shown.

3.6. Comparative analysis

Overall, the performance of the FAHP-TOPSIS algorithm applied to the allocation / selection of channels or spectral opportunities within the digital TV band, shows favourable results according to the retrieved occupancy data. The results obtained are similar to those delivered by the ideal allocation model while it far superior than the random allocation model, whose results for each performance metric are deficient in comparison to the ideal and proposed models.

Table 2 shows a comparative analysis of the quantitative data from each performance metric previously studied, throughout the 10 minutes of transmission.

Table 2. Comparison of the performance metrics for each model.

Algorithm	Average number of handoffs	Average number of failed handoffs	Average bandwidth (kHz)	Accumulative average delay (s) (10 MB)	Average throughput (kbps)
Perfect model	0	0	900	~10	4500
Proposed average	~40	~10	~820 (91%)	~60 (16,6%)	~4000 (88,8 %)
Random Selection	~360	~180	~100 (11%)	~580 (1,7%)	~500 (11%)

As seen in Table 2, the results of the proposed algorithm FAHP-TOPSIS reach performance levels of 90% in terms of bandwidth and throughput, taken as a reference the results of what corresponds to the ideal model. In the opposite case, the random algorithm presents a performance of 11% regarding the same metrics. In terms of the total handoffs, failed handoffs and accumulative average delay, these variables show a significant reduction with the FAHP-TOPSIS algorithm compared to the random model. Each metric shows a reduction of close to 90% compared to the random algorithm, marking the superiority of the proposed model.

4. Conclusions

The hybrid algorithm combining FAHP and TOPSIS for spectrum allocation uses the spectral occupancy matrix of the digital TV band as a basis. It reached results between 9% and 15% below the ideal solution which guarantees an adequate use of the spectral opportunities. The number of handoffs is strongly reduced compared to the experiments carried out in cell phone bands, having approximately 250 handoffs. This guarantees a better quality in user experience. However, a multi-user analysis is needed to determine the level of performance of the algorithm in response to the simultaneous requests for several spectral opportunities as well as the management of different types of applications that require more or less bandwidth. Thus, the attention capacity of secondary users can be measured in the digital TV band and the proposed allocation model.

Regulations approved for the opportunistic use of TVWS and defined by the FCC and Ofcom are mostly based on the geo-spatial database model. This, in addition to most references in literature, show that autonomous spectrum detection methods in cognitive systems can be explored as alternatives with potential opportunities ahead. Nonetheless, for this to become a fact in cognitive radio, exhaustive and detailed metering campaigns must be carried out to robustly characterize the spectrum and define clear and flexible regulations. The latter seeks to diminish spectral detection demands that cognitive devices must fulfil in order to gain access to the available opportunities within the TV band without affecting the communications of primary users.

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