redin Revista Facultad de Ingeniería, Universidad de Antioquia, No. 80, pp. 47-62, 2016

Fuzzy feedback algorithm for the spectral handoff in cognitive radio networks

UNIVERSIDAD DE ANTIOQUIA 1803

Algoritmo difuso realimentado para handoff espectral en redes de radio cognitivas

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ARTICLE INFO
Received January 28, 2016
Accepted September 19, 2016

KEYWORDS
Cognitive radio, decision making, feedback algorithms, spectrum mobility, vertical handoff

Radio cognitiva, toma de decisiones, algoritmo realimentado, movilidad espectral, handoff vertical

ABSTRACT: This work proposes a feedback algorithm based on a Fuzzy Analytical Hierarchical Process Method (FAHP) to improve decision making for the spectral handoff. We named it Feedback FAHP (FFAHP). To assess the performance level of the developed algorithms, a comparative analysis was made between the proposed FFAHP algorithm and the most relevant spectrum handoff algorithms in the current literature. These algorithms were assessed with the same decision criteria, which are, the probability of channel availability, estimated channel time availability, the signal to interference plus noise ratio and bandwidth. Unlike other related papers, benchmarking was validated through a trace of real spectrum occupation data captured in the frequency band GSM and Wi-Fi, which model the real behavior of primary users. In the validation phase, eight assessment scenarios were proposed to consider, two types of networks: GSM and Wi-Fi, two kinds of applications: real-time and best-effort, two traffic levels: high and low, and five evaluation metrics: number of handoffs, the number of failed handoff, bandwidth, delay, throughput. The results show that the proposed FFAHP Algorithm provides a performance improvement. The FFAHP Algorithm supplies an efficient and effective process for selecting frequency channels. The results indicate that the proposed FFAHP Algorithm provides a performance improvement. The FFAHP Algorithm supplies an efficient and effective method for selecting frequency channels. The results also show that the FFAHP Algorithm has a low average rate of handoffs, an effective use of the bandwidth, low delay and a high level of throughput; all these combined with the fact that the feedback implemented, stabilizes the system avoiding loops with consecutive hops to alternate frequencies.

RESUMEN: Este trabajo propone un algoritmo difuso realimentado basado en el método Fuzzy Analytical Hierarchical Process (FAHP) para mejorar la toma de decisiones para el handoff espectral. El algoritmo propuesto es denominado Feedback FAHP (FFAHP). Para evaluar el nivel de desempeño de los algoritmos desarrollados se realiza un análisis comparativo entre el algoritmo FFAHP propuesto y los algoritmos de handoff espectral más relevantes en la literatura actual. Estos algoritmos son diseñados con los mismos criterios de decisión, los cuales son: probabilidad de disponibilidad del canal, tiempo estimado de disponibilidad del canal, relación señal a ruido más interferencia y ancho de banda. A diferencia de los trabajos relacionados, la evaluación comparativa se validó a través de una traza de datos reales de ocupación espectral capturados en la banda de frecuencia GSM y Wi-Fi, que modelan el comportamiento real de los usuarios primarios. En la fase de validación se propusieron ocho escenarios de evaluación, al considerar, dos tipos de redes: GSM y Wi-Fi, dos clases de aplicaciones: tiempo-real y mejor-esfuerzo, dos niveles de tráfico: alto y bajo, y cinco métricas de evaluación: número de handoff, número de handoff fallidos, ancho de banda, retardo, Throughput. Los resultados muestran que el algoritmo FFAHP propuesto provee mejor desempeño. El algoritmo FFAHP provee un eficiente y

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ISSN 0120-6230
e-ISSN 2422-2844

DOI: 10.17533/udea.redin.n81a05

efectivo proceso para la selección de canales de frecuencia. Los resultados también muestran que el algoritmo FFAHP tiene una baja tasa promedio de handoff, un uso eficiente del ancho de banda, un bajo retardo de transmisión y un alto nivel de throughput; todo esto combinado con el hecho que la realimentación implementada estabiliza el sistema evitando bucles con saltos consecutivos a frecuencias alternativas.

1. Introduction

The new generation of networks comprises the integration of services, and the convergence of heterogeneous wireless networks. In order to achieve this integration, spectral mobility plays an important role in ensuring continuity of the communication and quality of service. In addition, the decision making mechanisms for spectral mobility in cognitive radio networks should make decisions based on the environment and with low delay. The spectrum mobility or spectral handoff (SH) is the process whereby a cognitive radio user (secondary user) changes its operating frequency for any of the following reasons according to [1-3] the target channel is being occupied by a primary user (PU), the arrival of a PU to a channel occupied by the secondary user (SU), the channel quality which is occupied by the SU is degraded, the SU interferes with the PU channel, and the variation of network traffic or the SU moves outside to the coverage area [4, 5].

With the wide range of technologies and wireless communication systems operating, it is essential to ensure spectral mobility between heterogeneous networks. The process by which an SU moves out of range of a base station to another base station in other network with different wireless technology is known as vertical handoff (VH) [6, 7]. This VH is developed from three main stages which are measurement, decision and execution [8]. In the measurement stage, the discovery and detection of wireless networks with their respective spectral opportunities are performed. This can be achieved through a centralized or distributed approach. In the decision stage, the decision making of "when" and "where" the VH should be performed is made. This decision is made based on multiple criteria and metrics that are previously selected. Finally, for the implementation stage, the transfer from the current connection to the new one is made taking into account the requirements of the aforementioned VH.

The spectral mobility has a significant impact on the performance of the cognitive radio networks; therefore, this work proposes a feedback algorithm to improve decision making for the spectral handoff. According to the VH strategy selected and configured, the performance of cognitive radio networks can be affected by factors such as, latency, throughput, signal to interference plus noise ratio (SINR), bandwidth [9], bit error rate, among others. According to current research, for example in [1-3, 10-14], VH decision making algorithm (VHDA) is the key feature to provide a continuous stream of SU data, because it could reduce the number of channel changes and latency during the SU transmission, thus, minimizing the channel degradation [10, 15]. There are currently several proposals for VHDAs. However, it is important to consider that the application of a specific VHDA strongly depends on the PU network characteristics [16].

This work proposes a novel VHDA based on the hybrid combination of the advantages of fuzzy logic and feedback systems. This algorithm improves decision making when selecting a spectral opportunity dynamically based on the following decision criteria (DC), the probability of availability of a channel (AP) [17], estimated time availability of the channel (ETA), the SINR and bandwidth (BW) [18, 19]. The proposed algorithm is based on the Fuzzy Analytical Hierarchical Process (FAHP) Method, which provides an adequate handling of vague information by using fuzzy logic. For the proposed VHDA, the hybrid algorithm stores the information of the assessments made in the past by the FAHP Method and feed them back as an additional criterion to the four previously mentioned. Therefore, the proposed hybrid VHDA model is named in this work as Feedback Fuzzy Analytical Hierarchical Process (FFAHP).

To assess the performance level of the proposed VHDA, a comparative analysis is performed with the most relevant spectrum handoff algorithms in the current literature. These VHDAs have been evaluated with the same four DC. Unlike other related papers, benchmarking was validated through a trace of real spectrum occupation data captured in the frequency band GSM (824 MHz to 849 MHz) and Wi-Fi (2.4 GHz to 2.45 GHz), which model the real behavior of primary users. In the validation phase, eight assessment scenarios were proposed to consider, two types of networks: GSM and Wi-Fi, two kinds of applications: real-time (RT) and best-effort (BE), two traffic levels: high (HT) and low (LT). Five evaluation metrics (EM) are performed: accumulative average number of handoffs (AAH), accumulative average number of failed handoffs (AAFH), average of transmission bandwidth (ABW), accumulative average transmission delay (AAD) and, (5) accumulative average transmission throughput (AAT).

The proposed FFAHP Algorithm is designed to provide a mechanism to make decisions for spectrum access in the context of cognitive radio, and therefore to provide the transitions from one frequency to other with minimal degradation of the communication, in order to ensure the continuity and quality of service.

The rest of the document is structured as follows. Section 2 shows a description of the most relevant related work. Section 3 describes the proposed FFAHP. In section 4 the simulation environment and experimentation are described. Section 5 presents the results obtained in the comparative analysis of the performance evaluation for the proposed VHDA. Section 6 presents the discussion of the results. Finally, conclusions are drawn in Section 7.

2. Related work

This section presents a summary of relevant work on algorithms for decision making in VH for cognitive radio networks (CRN).

The method for decision making based on multiple criteria (MCDM) has been the most widely used in research work on SH [20-24]. MCDM fundamental issues are diverse but share common characteristics, such as, alternatives to select the multiple DC describing the options, and a set of weights representing the relative importance of each DC [25]. Therefore, MCDM is a suitable mathematical tool for modeling the process of VH. Different MCDM methods have been proposed in the literature for the VH, such as, Simple Additive Weighting (SAW) [26], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [26], Multiplicative Exponent Weighting (MEW) [27], Grey Relational Analysis (GRA) [28], Elimination and Choice Translating Priority (ELECTRE) [29], Weighted Markov Chain (WMC) [30] and, Multi-criteria Optimization and Compromise Solution (VIKOR) [31]. For instance, the authors in [25] present an extensive comparative study of the MCDM methods previously mentioned. The performance of each method is evaluated under three different applications, voice, data and cost constraints. The authors also perform an analysis of the sensitivity of each method and its computational cost in terms of the number of floating point operations. The results show that the VIKOR and MEW algorithms have the best performance for the three applications tested.

One of the MCDM methods with better results found in the literature has been the Analytical Hierarchical Process (AHP) Algorithm. The AHP has proven to be effective for the evaluation and selection of spectral opportunities [20, 21, 28, 32]. The classical MCDM methods cannot efficiently solve a decision problem that contains vague information. However, fuzzy logic addresses this problem satisfactorily, and it can evaluate and combine multiple criteria simultaneously. The AHP complemented with fuzzy logic results in the FAHP Algorithm [6]. This combination improves the management of subjectivity and uncertainty on information and for the criteria assessments.

The authors in [33], used fuzzy logic to create a table for storing backup channels, thus when a handoff occurs, the secondary user can choose quickly one frequency channel available to continue the transmission and with handoff latency reduction. Because the PU arrival is uncertain, the availability of the chosen backup channel from the table is also uncertain. However, this possible uncertainty is minimized through frequent updating of the backup channels table. The results in [34], showed a reduction of the handoff delay and, the effective rate of data transmission by the SU is increased.

The authors in [34-36] proposed a network selection algorithm based on AHP and GRA. The AHP method is used to obtain the weights of each criterion. While the GRA method is used to organize from the best to the worst alternative. In [37, 38] the decision for the network selection is modeled through AHP and SAW. The AHP is also used to determine the weights of each selection criterion. While the SAW method is used to organize from the best to the worst alternative. In [21, 39] the network selection algorithm combines AHP and TOPSIS. The AHP calculates the relative importance of each criterion. While TOPSIS method is also used to organize from the best to the worst of each of the alternatives [40].

3. Design of the vertical handoff algorithms

Spectrum handoff models often have multiple variables to select channels, therefore, the MCDM methods are widely used in this type of problems where the relationship between attributes and selection criteria is measured by weights that are adjusted by the designer according to requirements. At the end of certain iterations, the best solution designed by the algorithm will be given. To benchmark the performance of FFAHP, six spectrum handoff models were selected: Simple Additive Weighting (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multi-Criteria Optimization and Compromise Solution (VIKOR), Multiplicative exponent weighting (MEW), Analytical Hierarchical Process (AHP), Fuzzy Analytical Hierarchical Process (FAHP).

3.1. SAW

This algorithm develops a decision matrix formed by attributes and alternatives, for each intersection of the matrix; the algorithm allocates a weight according to the designer criterion. This process establishes a description for each one of the graded SO thus, obtaining a ranking of all the alternatives. The SO with higher score will be selected [41, 42].

The alternative Ai is defined by Eq. (1) [43].

$$u_{\mathrm{i}} = \sum_{\mathrm{j=1}}^{\mathrm{M}} \omega_{\mathrm{i}} \mathrm{r}_{\mathrm{i,j}} \quad \forall i 1,\ldots,\mathrm{N} \tag{1}$$

Where $r_{i,j}$ belongs to the matrix and the sum of the weights is 1.

The steps to develop this algorithm are: (1) to identify the objectives and alternatives; (2) to evaluate the alternatives; (3) to determine the weights of each combination; (4) to add the added values based on the preferences; and (5) to analyze the sensibility [41-44].

In [45], SAW is used to select the best SO in a GSM frequency band, evaluating the quantity of handoff implemented and comparing the results with other two SA algorithms

3.2. MEW

MEW is other MCDM algorithm is similar to SAW. The main difference is that in MEW instead of addition there is multiplication. It was proposed for SA in [27]. In MEW the SO qualification is defined by the product of the weights of the decision criteria. The S_i score of the i SO is determined by the Eq. (2) [25, 27, 41-45].

$$S_i = \prod_{j \in N} x_{ij}^{wj} \quad (2)$$

Where x_{ij} denotes the j criterion of the i SO, w_j indicates the j criterion weight, and $\sum_{j=1}^{N} w_j = 1$. It is necessary to take into account that in (2) w_j is a positive power for profit metric and negative for a cost metric.

In [46] MEW is used to select the best SO in a frequency band of mobile communications, evaluating the Throughput process and bandwidth and, comparing the results with the ones of SA algorithms.

3.3. TOPSIS

The development of this algorithm is based on the determination of two components: the ideal solution of the system and the solution that cannot be accepted in any scenario. To achieve it, it is necessary to compare the obtained results to define what solution is the closest to the ideal one, and which one is the furthest (which is not going to be accepted). That metric is obtained from the Euclidean distance [41, 42].

TOPSIS algorithm procedure is described in [41-43]. Initially, and X decision matrix is designed and normalized using the square root method, then, the best and worst solution are defined. Subsequently, for each alternative, the Euclidean distance D is calculated, finally, the alternatives are organized in a descending way based on the preference rate given by Eq. (3).

$$C_i^+ = \frac{D_i^-}{D_i^+ + D_i^-}, \quad i = 1, \ldots, N. \quad (3)$$

In [47] TOPSIS is used to select the best SO, evaluation the interference level for adjacent channel and average number of made handoff, the results are compared with other algorithm and its respective versions when combined with three prediction algorithm based on time series.

3.4. VIKOR

"VIKOR method assumes that every alternative has to be evaluated based on every criterion function and the classification could be developed through a comparison among the measures that are closer to the ideal alternative" [47-49]. VIKOR was developed to fulfill the optimization of complex systems with multiple criteria, hence, it is able to delimit the compromise on a ranking list, still in presence of the conflicting criteria what makes an algorithm suitable to make decisions in SA [50].

VIKOR algorithm follows the steps described in [25, 42, 46, 48]. For each decision criterion, the best and the worst value are delimited taking into consideration if they are profits or costs.

Then, the Q_i values are calculated for i= 1, 2, 3, M given by Eq. (4).

$$Q_i = \gamma\left(\frac{S_i - S^+}{S^- - S^+}\right) + (1-\gamma)\left(\frac{R_i - R^+}{R^- - R^+}\right) \quad (4)$$

Given the Q values for all the i belonging to M, the SO candidates are classified from high to low. Finally, the selected SO is given by the ideal Q.

In [48], VIKOR is used to select the best SO in the ascending link in the GMS frequency band, evaluating the handoff block level and comparing the results with other SA algorithms.

3.5. AHP

AHP is based on comparisons about the importance between the chosen criteria decision for the selection of an alternative, being this more a relative measurement than an absolute value [51].

In the design methodology of the AHP algorithm, the first step is to define the problem, breaking it into objective, criteria and alternatives. The second phase is the construction of a hierarchy in agreement with the definition of the problem.

Once constructed the hierarchy, the matrix judgments were carried out, which correspond to the benchmarking that define the relative importance level in each possible combination of criteria couples. With the matrix judgments defined, it finally proceeds to calculate the normalized weights for each criterion, as it is defined in the Eq. (5) [41].

$$r = [r_1, r_2, \ldots, r_n] \; con \; r_i = \frac{v_i}{\sum_{j=1}^{n} v_j} \quad (5)$$

Where r is the vector of own values, $r_1, r_2, \ldots r_n$ is the value of the weights of each subcriterion V_i is the geometric mean of i row, And V_j is the geometric mean of j column.

In [41] AHP is used to select the best So in the GSM frequency band, calculating the performance of the algorithm based on five evaluation metrics and comparing the results with another five SA algorithms.

3.6. FAHP

Fuzzy logic is a particularly suitable tool to take decisions in scenarios where all the open entrances are in general uncertain and imprecise or qualitatively interpreted. Fuzzy logic can also transform qualitative and heterogeneous information into homogeneous membership values, which can be processed through a set of appropriate fuzzy inference rules [1-3, 25, 27, 41-60]. These advantages of the fuzzy logic are combined with AHP algorithm, obtaining the FAHP method [23, 61].

Although the FAHP method has, in essence, the same methodology as the AHP algorithm, the fuzzy logic helps to process the subjectivity and the uncertainty in the criteria evaluations, since the fuzzy logic, through a mathematical process, allows using a range in the answer instead of a concrete number [1-3, 23, 25, 27, 41-60]. In the FAHP algorithm, after the normalization, the weight vector is given by Eq. (6).

$$W=(d_1,d_2,\dots,d_n)^T=\left(\frac{d_1}{\sum_{i=1}^{n}d_i},\frac{d_2}{\sum_{i=1}^{n}d_i},\dots,\frac{d_n}{\sum_{i=1}^{n}d_i}\right) \quad (6)$$

Recently the FAHP algorithm has been widely used to answer multi-criterion decision problems in several areas. In [41,52] FAHP is used to carry out SA in CRN.

3.7. The proposed FFAHP

The proposed FFAHP Algorithm aims to increase the accuracy in the selection of the spectral opportunity by feeding back the information from past evaluations. The selection of the spectral opportunity is made based on the evaluation of the current spectrum information plus past evaluations.

Initially for the FFAHP Algorithm, the capture process takes samples of frequency, power and time. The amount of data captured depends on the parameters of resolution bandwidth, span and sweep time, which are set in the spectrum analyzer utilized [62]. The captured data is stored in a database. Periodically, the information processing unit calculates the value of the DC, for our case study, AP, ETA, SINR and BW, and then the DC are normalized. The FFAHP receives each of the DC values updated and, it evaluates each available spectral opportunity. If the algorithm is using the RT application, then apply the Eq. (7), and for the BE application the Eq. (8) is used.

$$Score_i = AP\times 0.3593 + ETA\times 0.2966 + SINR\times 0.1970 + BW\times 0.1471 \quad (7)$$

$$Score_j = AP\times 0.1607 + ETA\times 0.1523 + SINR\times 0.3949 + BW\times 0.2921 \quad (8)$$

Where $Score_i$ is the score assigned to the spectral opportunity i for a RT application, and $Score_j$ is the score assigned to the spectral opportunity j for a BE application. The evaluation score range is between 0 and 100, with 100 being the best possible score. Figure 1 illustrates the design of the FFAHP Algorithm.

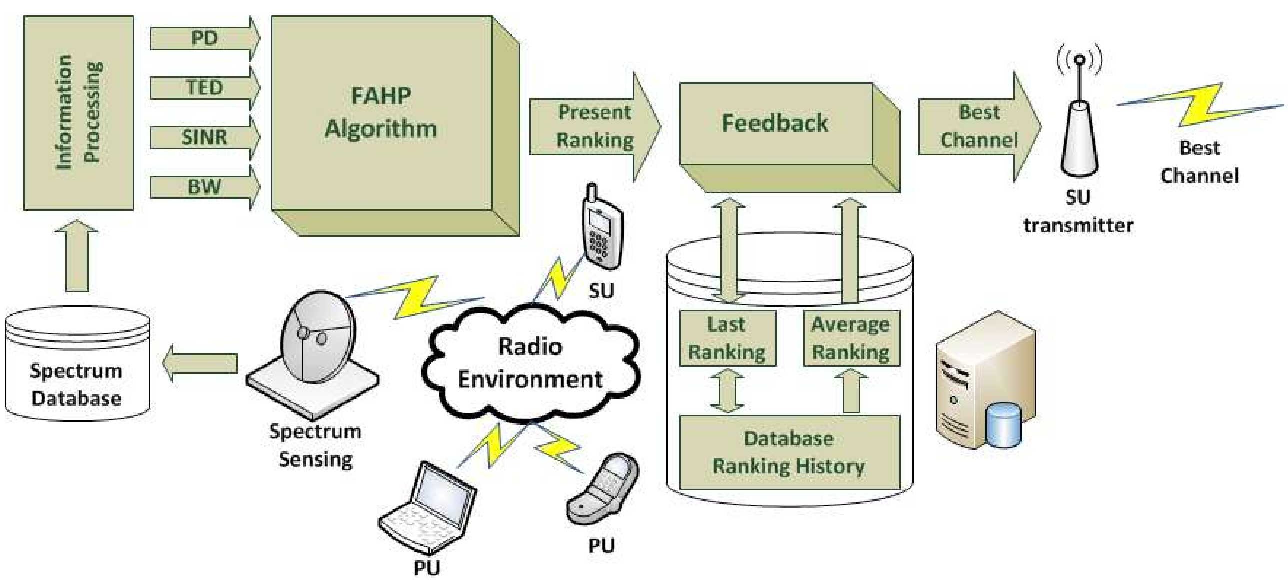

Figure 1 The scheme of the proposed FFAHP

In this stage of the process, it is obtained a ranking of each of the spectral opportunities available based only on the current information regarding the DC. However, the opportunity with the best assessment at this moment may not be the final selection, because this evaluation is weighted with evaluations in the past. The feedback process receives current assessments (CA) of each spectral opportunity and it weighs them up with the last evaluation (LE) and with the average evaluations (AE) which are carried out in the last minute. This weighting results in the final ranking of spectral opportunities as expressed in Eq. (9).

$$Final\_Score_i = \alpha \times CA + \beta \times LE + (1-\alpha-\beta)\times AE \quad (9)$$

Where α and β ϵ [0,1] characterize the weighting of CA, LE, and AE, and then, the $Final\_Score_i$ is the result of the final evaluation of the spectral opportunity i. The spectral opportunity with the best final evaluation is selected for the data transmission of the SU. Subsequently, the feedback process transfers the value of the CA to the LE and updates the value of the AE according to the new value of LE. If the spectral opportunity finally selected is occupied, the FFAHP Algorithm overwrites the LE value.

To determine the values of α and β, an autoregressive experimental analysis with different combinations of α and β was performed; this for a predetermined set of data. The values of α and β were taken for which the accuracy in the selecting spectral opportunity was the highest. These values correspond to α = 0.60 and β = 0.35, with an experimental accuracy of 87%.

4. Experiments and simulations

In order to assess the performance of each developed VHDA, a simulation environment progressively reconstructs the behavior of the spectrum occupancy with the use of the captured data traces in the frequency GSM band. These allows to accurately evaluate the behavior of the PUs and also, to assess and validate the performance of each VHDA. The spectral occupancy data corresponds to a week of observation captured at Bogota City in Colombia [62]. The energy detection technique was used to determine the occupation or availability of the analyzed GSM and Wi-Fi band, with a decision threshold for the power of 5 dBm above the noise power. To determine whether a frequency channel is busy or not, the proposed decision threshold is based on the average noise floor for the frequency band used. We consider the specifications of the GSM and Wi-Fi band, the standard configuration of the spectrum analyzer and the measurements to establish the noise floor and the guard level. The average noise floor is obtained by the spectrum analyzer measurements. The guard level was fixed at +5 dBm for above of the noise floor, in order to minimize false alarms. Thus, the average noise floor is -113 dBm and the decision threshold is set to -113 + 5 = -108 dBm.

The equipment for the spectral measurements are comprised by the Discone Antenna in a frequency range from 25MHz to 6 GHz, a low noise amplifier (LNA) in the frequency range of operation between 20 MHz and 8 GHz and a Spectrum analyzer in the frequency range of operation between 9 kHz and 7.1 GHz. The main technical parameters for the spectral captured data are: frequency band between 824 MHz and 849 MHz for a GSM Mobile communication system, and between 2.4 GHz and 2.45 GHz for Wi-Fi. The capturing time was set to 1hour. The resolution bandwidth

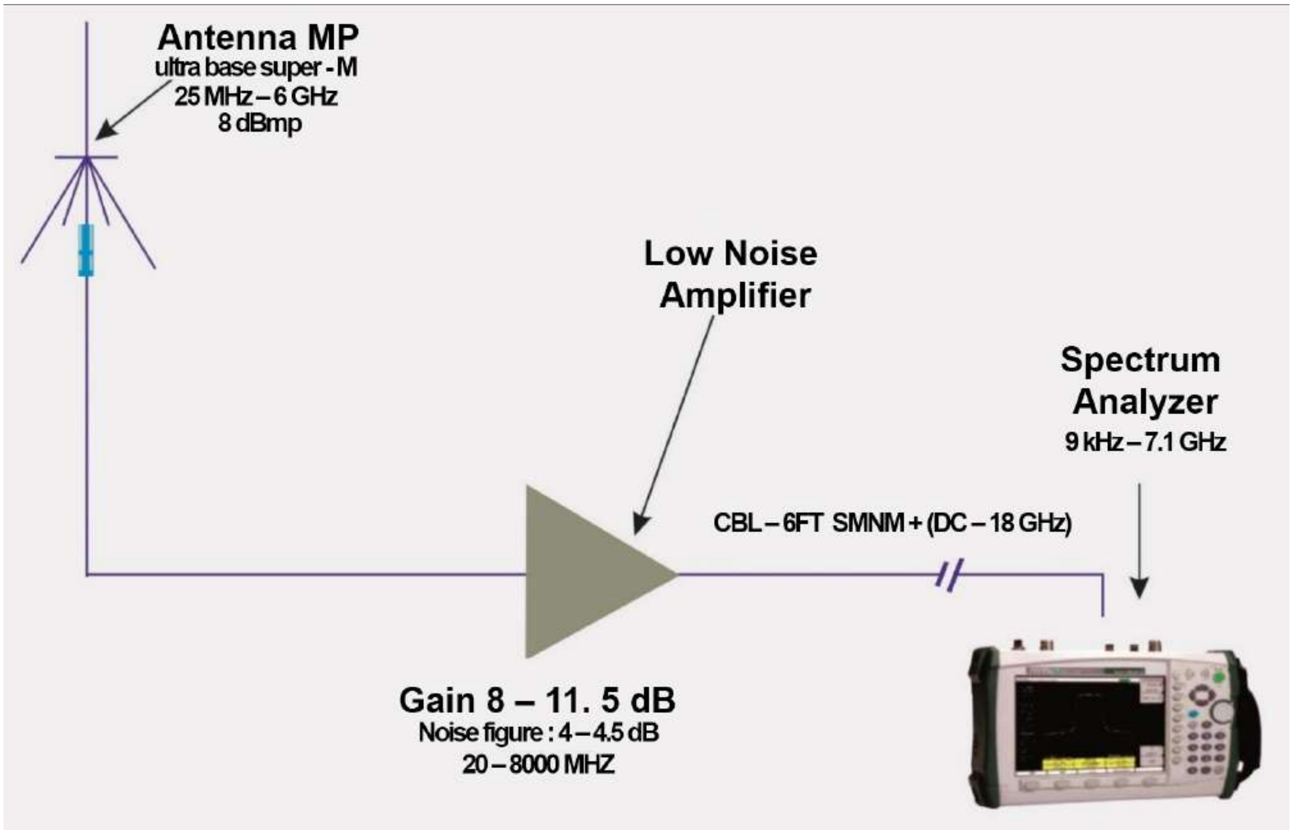

Figure 2 Experiment setup to capture the data from the spectrum [62]

was set to 100 kHz, the span to 50 MHz and the sweep time was of 333ms. The diagram with the setup of the equipment used for the capturing process is shown in Figure 2.

The captured data were organized and preprocessed to obtain the corresponding values of the sub-criteria per channel. Once captured spectral occupation data, a pre-processing of the data was performed, this is in order to calculate the values of each of the determined sub-criteria in the hierarchy. Then, the different traces of spectrum occupancy obtained by the spectrum analyzer are unified. This includes a comprehensive database for the calculations in the evaluation process of the developed FFAHP Algorithm.

Using the information of channel availability of each channel versus time, an analysis of the traffic as a function of time and day of the week was made. The channel availability is represented by "1" and the occupation with "0". Then, the average number of simultaneously active PUs over the frequency channels was analyzed and, a sub-set of spectral information corresponding to an hour with average active PUs was selected. This sub-set was complemented with information from the four DC, i.e., AP, ETA, SINR and BW, and used for evaluation and validation of the three VHDAs. The magnitude of the AP variable corresponds to the standard duty cycle of the selected frequency channels. For the ETA variable, the times that each channel remained continuously available were calculated and averaged. The SINR variable is calculated from the average of the ratio between the signal power and the average value of the noise floor. Finally, since BW has a constant value for each frequency band, it was decided to gather dynamically the four adjacent channels on each side of every channel, as long as they were available (see Eq. (10)).

$$BW_i = BW_{i-4} + ... + BW_{i-1} + BW_i + BW_{i+1} + ... + BW_{i+4} \quad (10)$$

Once calculated the estimated value of each of the selected DC, these are normalized, in order to balance the percentage of importance, between the highest and the lowest values. All values of the DC were adjusted to a range from 0 to 100.

A data base with information of the spectrum was built and, using Matlab simulations, the performance of each VHDA from selected frequency channels in real time were evaluated. The database provides only the spectral information corresponding to the instant of time (τ) which is running in the simulation. To avoid affecting the validity of the database information, each of the estimated value of the DC were progressively constructed from the previous spectral information at time τ.

In agreement to the simulation design, if one of the selected VHDA implemented in the system wishes to transmit during φ minutes, it should follow the methodology described as follows. First, the simulation updates the value of the DC based on the stored information previous to the time τ. Second, it makes a ranking with the classification of the channels according to the methodology of each VHDA, which in turn is based on the score obtained by each channel from Eqs. (3) and (4). Third, the VHDA selects the best channel of the ranking to start transmission. Fourth, at the time τ_0, it is verified on the database, if the selected channel is available at this time, in the case that it is available, the process goes to the fifth step; otherwise, a failed handoff occurs and the second channel of the ranking is selected and the process return to the fourth step. It is important to remark that the VHDA only knows the probability of finding the channel available (AP), which is different from the real time information of availability. Fifth, the simulation continuously verifies in the database, if the selected channel is still available. Sixth, at the time τ_k, if the selected channel is occupied by a PU, i.e., the channel is no longer available as indicated in the database, and if $\Delta\tau = \tau_k - \tau_0$ is smaller than 60 seconds, then, the second ranked channel is selected and, the process returns to the fourth step. Otherwise, the simulation returns to the first step and τ_0 is updated with the current time. Seventh, if during γ seconds is not possible to find an available channel, the communication is missing. This procedure repeats until the φ minutes of transmission are completed or until the communication stops.

During the simulation execution, the information is stored for five EM: AAH, AAFH, ABW, AAD and AAT. After running several periods of simulation for each VHDA, the average values of the five EM are calculated and the comparative analysis is performed. For each VHDA, independent simulations are run for the eight scenarios: GSM-RT-LT, GSM-RT-HT, GSM-BE-LT, GSM-BE-HT, Wi-Fi-RT-LT, Wi-Fi-RT-HT, Wi-Fi-BE-LT, Wi-Fi-BE-HT.

5. Results

This section provides a comparative analysis of the performance of each of the VHDAs presented, the proposed FFAHP contrasted to the six MCDM Algorithms. The results are organized into six sub-sections based on the EM, (A) AAH, (B) AAFH, (C) ABW, (D) AAD, (E) AAT, and (F) the comparative analysis of the VHDAs.

5.1. AAH

Figure 3 describes the AAH that were presented in each spectrum handoff model during a 10-minute transmission, in GSM and Wi-Fi band, for a high and low traffic trace, with RT and BE approaches.

5.2. AAFH

Figure 4 describes the AAH that were presented in each spectrum handoff model during a 10-minute transmission, in GSM and Wi-Fi band, for a high and low traffic trace, with RT and BE approaches.

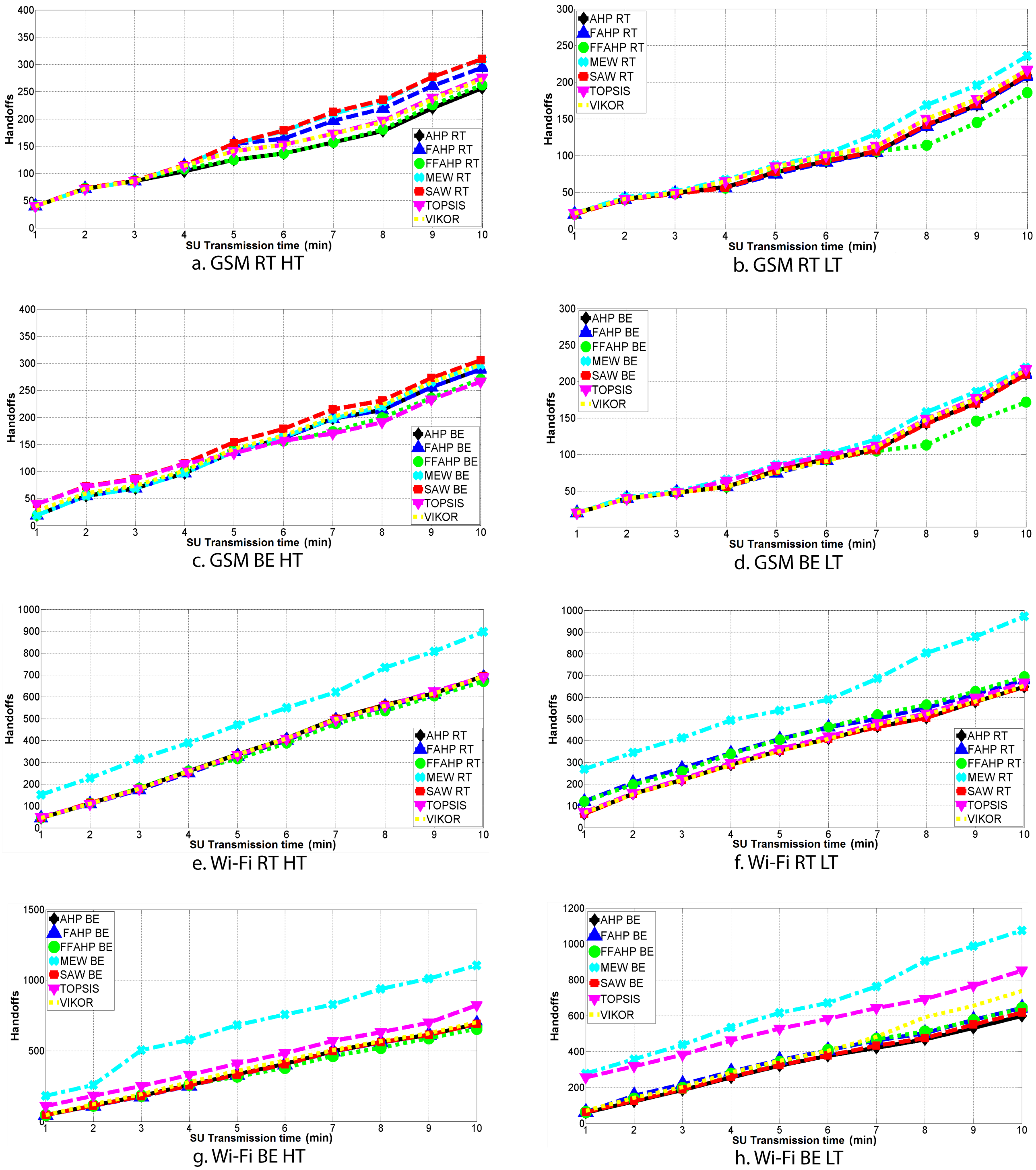

Figure 3 AAH for a) GSM-RT-HT, b) GSM-RT-LT, c) GSM-BE-HT, d) GSM-BE-LT, e) Wi-Fi-RT-HT, f) Wi-Fi-RT-LT, g) Wi-Fi-BE-HT, h) Wi-Fi-BE-LT

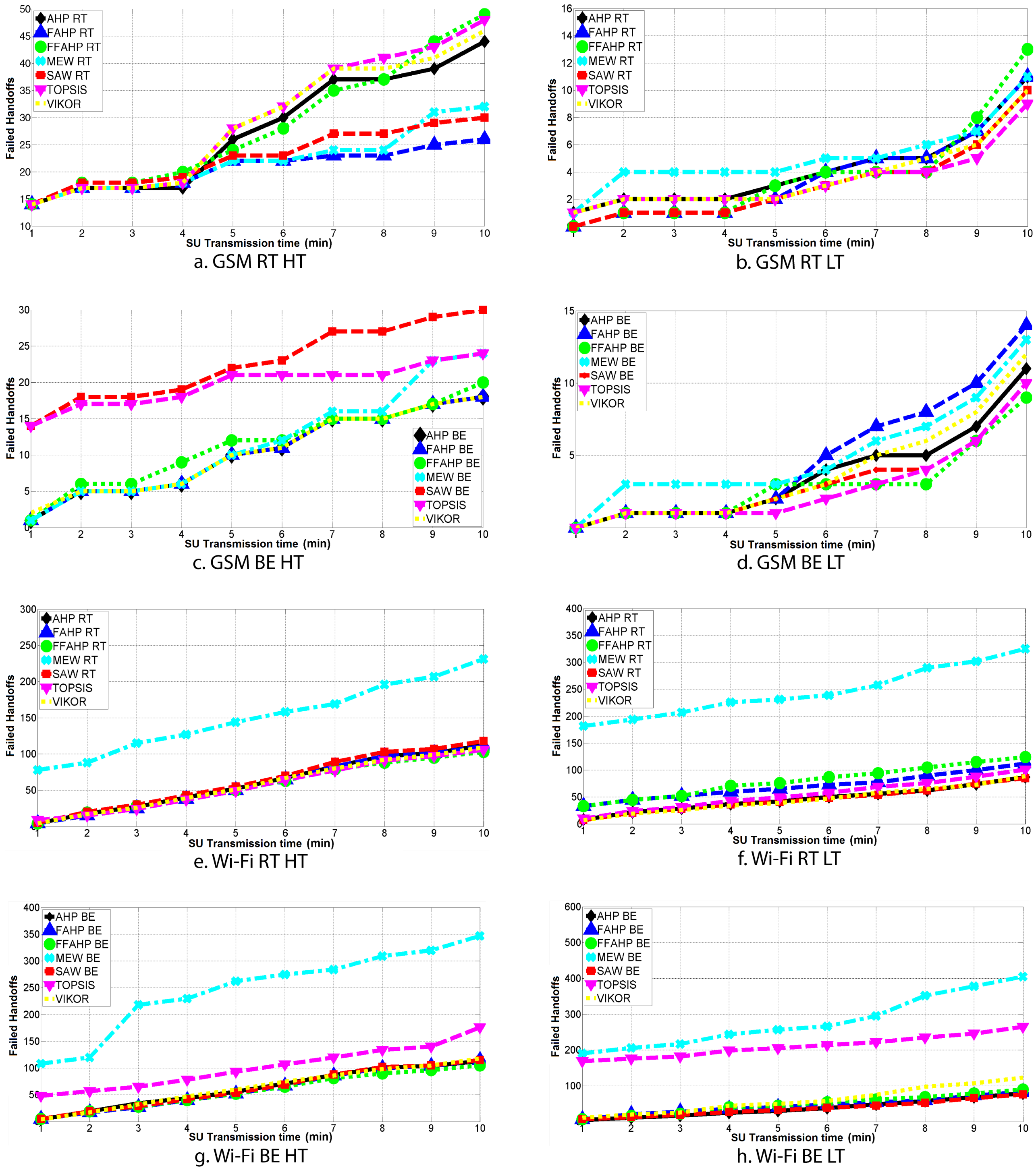

Figure 4 AAFH for a) GSM-RT-HT, b) GSM-RT-LT, c) GSM-BE-HT, d) GSM-BE-LT, e) Wi-Fi-RT-HT, f) Wi-Fi-RT-LT, g) Wi-Fi-BE-HT, h) Wi-Fi-BE-LT

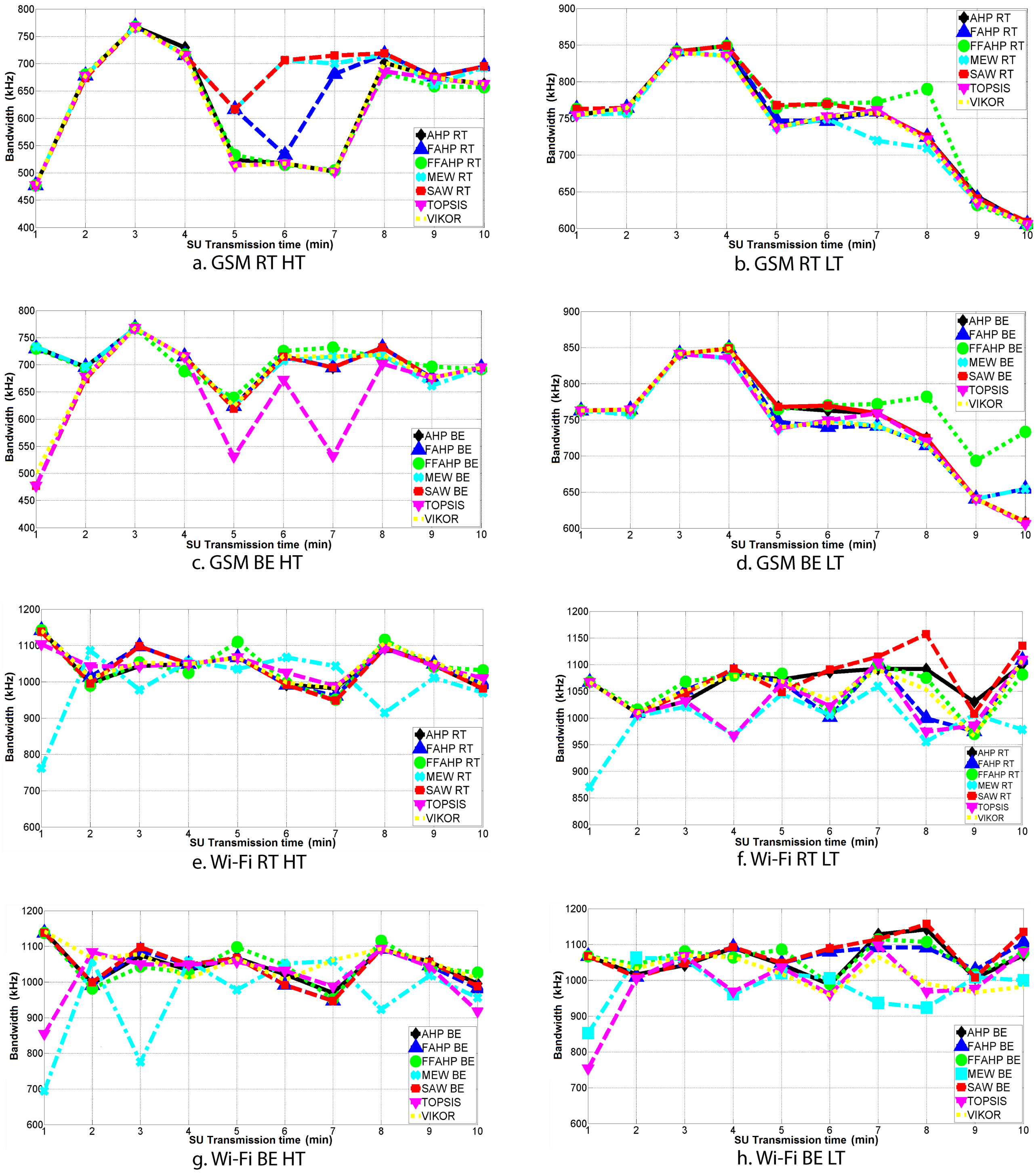

Figure 5 ABW for a) GSM-RT-HT, b) GSM-RT-LT, c) GSM-BE-HT, d) GSM-BE-LT, e) Wi-Fi-RT-HT, f) Wi-Fi-RT-LT, g) Wi-Fi-BE-HT, h) Wi-Fi-BE-LT

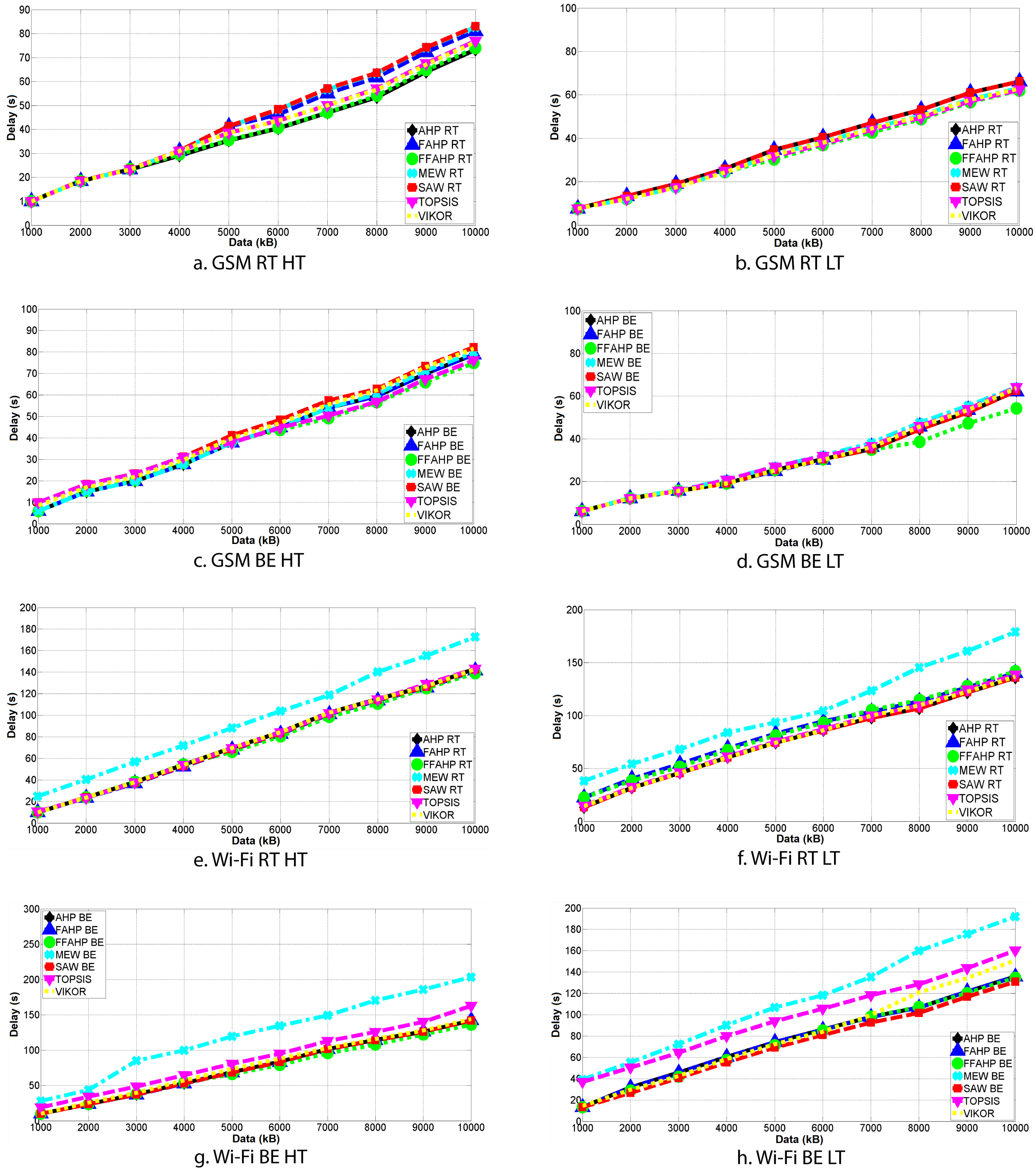

Figure 6 AAD for a) GSM-RT-HT, b) GSM-RT-LT, c) GSM-BE-HT, d) GSM-BE-LT, e) Wi-Fi-RT-HT, f) Wi-Fi-RT-LT, g) Wi-Fi-BE-HT, h) Wi-Fi-BE-LT

5.3. ABW

Figure 5 describes the AAH that were presented in each spectrum handoff model during a 10-minute transmission, in GSM and Wi-Fi band, for a high and low traffic trace, with RT and BE approaches.

5.4. AAD

Figure 6 describes the AAH that were presented in each spectrum handoff model during a 10-minute transmission, in GSM and Wi-Fi band, for a high and low traffic trace, with RT and BE approaches.

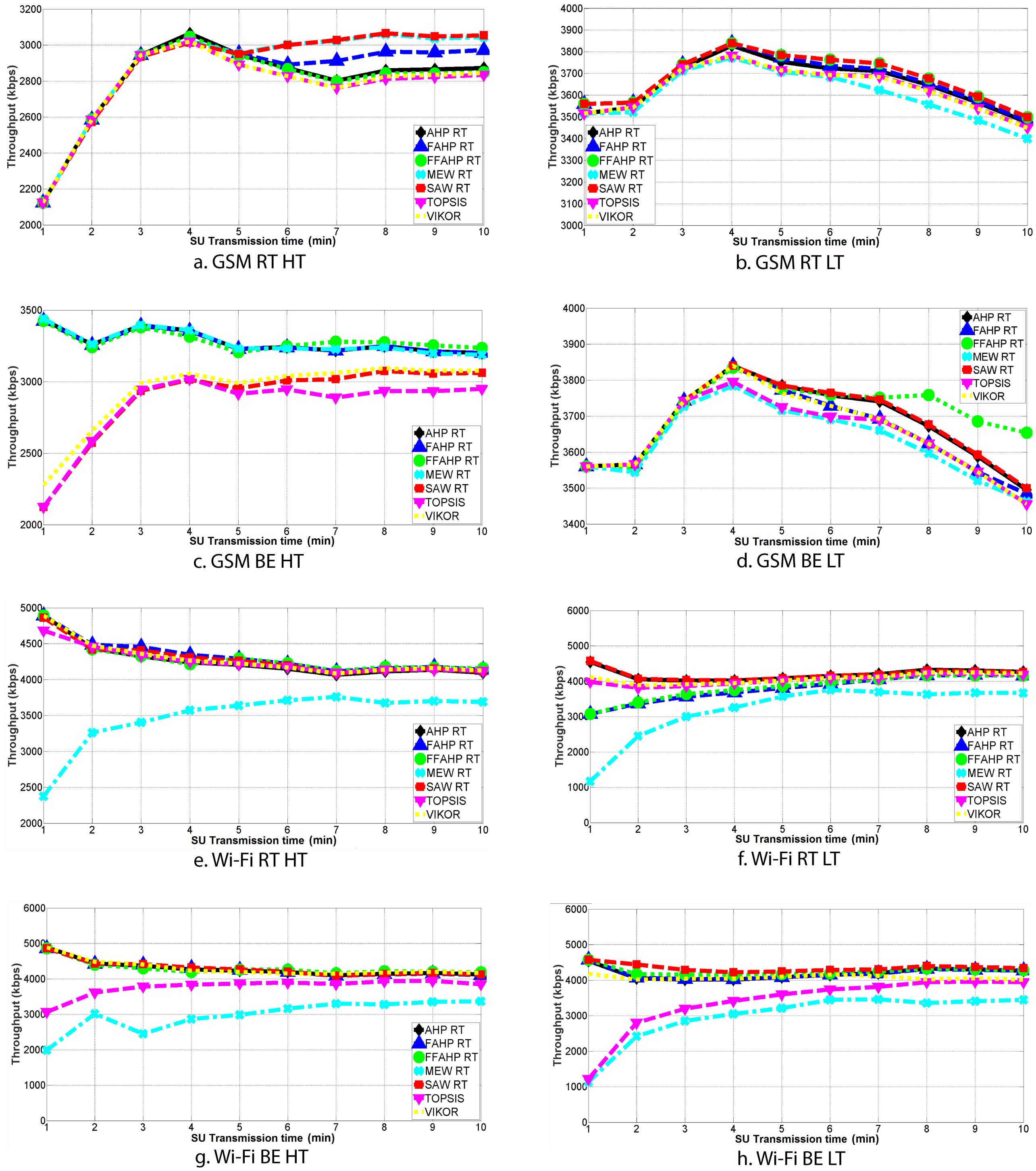

Figure 7 AAT for a) GSM-RT-HT, b) GSM-RT-LT, c) GSM-BE-HT, d) GSM-BE-LT, e) Wi-Fi-RT-HT, f) Wi-Fi-RT-LT, g) Wi-Fi-BE-HT, h) Wi-Fi-BE-LT

5.5. AAT

Figure 7 describes the AAH that were presented in each spectrum handoff model during a 10-minute transmission, in GSM and Wi-Fi band, for a high and low traffic trace, with RT and BE approaches.

5.6. Comparative analysis of the VHDAs

The Tables 1 and 2, show the comparative performance percentages in each algorithm by EM, as for GSM network as Wi-Fi.

Table 1 Global benchmarking by EM for GSM network

EM	MEW	SAW	TOPSIS	VIKOR	AHP	FAHP	FFAHP	RA
AAH	83.3	85.89	90.37	88.02	91.5	88.52	100	10.63
AAFH	88.79	94.38	92.21	92.89	93.24	100	90.22	1.38
ABW	100	99.8	96.01	97.31	98.62	99.78	99.77	64.54
AAD	91.52	90.17	94.65	93.03	94.04	91.83	100	17.68
AAT	99.18	99.25	95.89	96.98	98.62	99.42	100	45.07
Global Score	93.64	93.99	94.28	93.96	95.74	95.17	99.7	34.25

Table 2 Global benchmarking by EM for Wi-Fi network

EM	MEW	SAW	TOPSIS	VIKOR	AHP	FAHP	FFAHP	RA
AAH	65.47	99.29	87.85	94.58	100	97.27	98.7	58.84
AAFH	31.38	100	70.66	89.3	99.26	92.12	92.5	34.36
ABW	92.62	100	96.52	98.66	99.36	99.1	99.43	87.43
AAD	74.11	100	91.62	96.02	98.93	98.48	99.9	71.08
AAT	84.2	100	95.68	98.23	99.56	99.04	99.71	79.42
Global Score	78.25	99.84	92.49	96.74	99.44	98.34	99.28	73.58

6. Discussion

Analyzing the VHDA FFAHP performance, along with the most relevant algorithms, selected from the current literature, such as: FAHP, VIKOR, TOPSIS, SAW, MEW y AHP, it is observed that regarding AAH (Figure 3), FFAHP has the best performance in GSM with a wide margin; while in Wi-Fi the best one is SAW, followed very closely by AHP and FFAHP. Regarding AAFH (Figure 4), it is observed that FAHP has a better performance in GSM, while in Wi-Fi the best is SAW, followed by AHP. Concerning ABW, (Figure 5), it is observed that MEW has the best performance in GSM, followed by SAW, FAHP, and FFAHP, while in Wi-Fi the best one is SAW, followed closely by FAHP, FAHP, AHP y VIKOR. Regarding AAD (Figure 6), it is perceived that FFAHP has the best performance in GSM with a wide margin, while in Wi-Fi the best one is SAW, followed closely by FFAHP. Concerning AAT (Figure 7), it is observed that FFAHP has the best performance in GSM, followed closely by FAHP and SAW; while in Wi-Fi the best one is SAW, followed closely by FFAHP, FAHP y AHP.

For the GSM case, given the reduced difference it can be stated that FFAHP algorithm is the dominant algorithm for the four scenarios (RT-HT, RT-LT, BE-HT, BE-LT). In the case of an analysis by EM (Table 1) for applications sensitive to delay the best algorithm is FFAHP, but if high throughput level is required the most appropriate one is SAW, in the case of requiring both the best combination has it FFAHP.

For the Wi-Fi case, it is concluded that in high traffic scenarios the best algorithm is FFAHP, while for low traffic scenarios t e ideal one is SAW, In the case of an analysis by EM (Table 2), SAW is the algorithm most appropriate as for applications sensitive to delay as the ones that require a high throughput level, only in the case of HT for applications sensitive to delay that do not require a high throughput level, FFAHP has a better performance than SAW.

Finally, analyzing the results in Tables 1 and 2, it can be concluded when the performance level is carried out in each EM of each VHDA, FFAHP algorithm has the best global score, making it in the best candidate to select a spectral opportunity.

7. Conclusions

A new algorithm, which includes a feedback method, for decision making in cognitive radios is proposed in our work. Based in the Fuzzy Analytical Hierarchical Process (FAHP), we named it the Feedback FAHP (FFAHP). The decision criteria were carefully chosen to enhance the performance of, real-time and best-effort selected applications. This work also presents a performance evaluation and comparative analysis of the proposed FFAHP and six more algorithms of decision making used for the vertical handoff in cognitive radios. These algorithms are based on multiple-criteria decision making (MCDM) type of algorithms. The evaluation and validation of the three algorithms is made by means of extensive simulations, using real experimental data of the spectrum occupancy. These data have been captured at the GSM mobile band. Then, the simulations present an environment which models the occupancy behavior of the licensed users and the GSM and Wi-Fi frequency spectrum.

The performance evaluation of the six algorithms for the decision making of the vertical handoff was performed using four evaluation metrics. These metrics are accumulative average of performed handoffs, the accumulative average of failed handoffs, the average of transmission bandwidth, accumulative average of the transmission delay, and accumulative average of the transmission throughput.

The proposed FFAHP, performs efficiently in both types of applications tested, real-time and best-effort. The simulation results show that FFAHP has low average of, handoffs and delay, and high rate of, bandwidth and throughput. The proposed FFAHP Algorithm provides efficient and effective process for selecting frequency channels for cognitive radios. In addition, the comparative analysis shows that for the best-effort applications, the FFAHP Algorithm is significantly better for decision making than the other two algorithms evaluated.

8. Competing Interest

The authors declare that they do not have competing interests.

9. Acknowledgements

The authors wish to thank for support of this research work to, Universidad Distrital Francisco Jose de Caldas; Universidad Nacional de Colombia; Secretary of Foreign Affairs of the Mexican Government; Autonomous Metropolitan University – Iztapalapa.

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