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Evaluation of the Failed Handoff Rate in Collaborative Wireless Networks

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Abstract

Cognitive radio is an essential technology to overcome fixed spectrum allocation problems and improve its use through dynamic spectrum access techniques. Spectral decision-making is a function of the cognitive cycle that aims to choose the best spectral alternative among a set of finite possibilities. An inadequate process of decision-making can significantly affect the network parameters. Therefore, it is important to determine the best strategy and if this decision making should be collaborative. The present research analyzes the performance of failed handoff rate according to the amount of information shared between secondary users. The aforementioned information corresponds to the spectral occupancy for the GSM frequency band, that is characterized by a set of users and five levels of collaboration, 10%, 20%, 50%, 80% and 100%, where each level represents the percentage of users are part of the training model implemented. The decision-making process is carried out by using two multi-criteria techniques: Feedback Fuzzy Analytical Hierarchical Process (FFAHP) and Simple Additive Weighting (SAW). Based on the obtained percentage ratios and the information shared, it is determined that for the given number of failed handoffs, the level of collaboration that leads to efficient results is between 20% and 50%.

Keywords: Collaborative work, Decision-making, Multiuser channels, Radio communication

1 Introduction

Cognitive radio (CR) is a smart technology that can efficiently solve limited access issues in wireless networks. The concept was created by Joseph Mitola III in 1999 and several entities such as the IEEE, the International Telecommunications Unit (ITU) and the National Telecommunications and Information Administration (NTIA) have come to terms with a general definition [1–6].

The main principle of CR consists on granting access to the spectrum through a dynamic strategy, through the opportunistic exploration in the space-time dimensions of the network. In contrast with traditional networks, there are two types of users in CR. The licensed or primary user (PU) has a license to use frequency bands and the secondary user (SU) that makes opportunistic use of the spectrum while it is still available [6–10].

Cognitive radio networks (CRN) operate with a management model that performs smart adaptations, based on progressive learning and information exchange [11] to implement a dynamic and opportunistic access method. Spectrum decision-making is a key function of CRN. However, it has not been as researched in comparison to other functions of the cognitive cycle [7, 12–14]. The decision-making process aims to choose the best spectral opportunity among a finite set of possibilities, allowing the SU to generate a sequence of actions that will lead to the completion of its objectives [13–16]. An inadequate decision-making process can significantly affect the parameters of quality, latency, throughput, reliability, signalization, PU interference, energy efficiency, bandwidth, SINR and error rate [2, 17–20]. Therefore, a proper decision making process it is required.

Collaborative strategies have delivered new models for the efficient use of radio resources, as well as the decision-making process for CRN. In collaborative decision-

making, users can communicate between them to exchange local measurements regarding availability and interference, as well as other variables [14]. The purpose is to take advantage of spatial diversity which is achieved by the collaborative of unlicensed users who share information with neighbors [21]. The collaborative approach offers more advantages than the non-collaborative approach because the diversification of the observation of the spectrum avoids possible interference. A challenge in spectrum selection is the way in which the information from collaborative users is combined while the transmission is carried out [22].

The decision making processes based on collaborative models allow the use of different techniques, under probabilistic models. In [23], secondary users are classified into two levels: users in real time (RT) and users in non-real time (NRT). This enables to study the conflict and cooperation between both levels that make use of game theory. An auction game-based model is proposed that analyzes the decision-making process. The results show that a high number of secondary users is catered along with the reduction of user blockage probability, user handoff and channel saturation, as well as an increase in the probability of user acceptance.

In order to overcome the hidden terminal matter that a SU could face [24], an incentive-based framework is proposed that adopts a reputation strategy, where the problem of collaboration is modeled as an indirect reciprocity game. The results obtained with the strategy show that the proposed scheme achieves proper performance.

Another type of strategy uses techniques based on logical statements. In [25] a collaborative decision-making process is proposed that uses fuzzy logic. The decision-making criterion works with relative link quality (RLQ) and signal plus interference noise ratio (SINR). The model uses fuzzy logic rules based on the fuzzy interference system

(FIS). Finally, due to low complexity and response times, the proposed strategy is characterized by being easily implemented in real systems.

Algorithms based on multi-criteria decision-making (MCDM) are widely used for the decision making processes based on collaborative models. They operate using weight allocation, which are adjusted according to certain requirements. [26] compares the performance of four algorithms for spectral occupancy of the PU during the communication with a SU. The performance of the algorithms is assessed using five metrics: handoffs, failed handoffs, bandwidth, delay and throughput.

The decision-making process requires the work of spectral occupation data that can be generated randomly or obtained through measurements. The collected data is used to train and validate the models. However, using few data can lead to inefficient decisions and gathering many data can incur in significant computational costs and delays.

To obtain an efficient decision-making process, with no computational costs. The research work presented analyze the decision making under collaborative scenarios in order to obtain on where users share different amounts of spectral occupancy information. According to the results obtained in [26], metrics such as number of failed handoffs are used in order to measure performance collaborative decision-making process

Information is characterized by five levels of collaboration (10%, 20%, 50%, 80% and 100%) where each level represents the percentage of information that is shared for training and subsequent validation of the model. The levels are chosen according to the limits of the data where 10% and 100% correspond to the criteria of few data and excessive data respectively. 50% corresponds to the intermediate value of the limits, and, the levels of 20% and 80%, comprises the interval to analyze the collaboration within an information range.

For the analysis of the decision making proposed, a collaborative algorithm is designed to segment the matrix according to five levels of collaboration. The decision-making process is based on two multi-criteria (MCDM) techniques: Feedback Fuzzy Analytical Hierarchical Process (FFAHP) and Simple Additive Weighting (SAW) [2, 15, 16, 27–29]. As part of the decision-making process, the connection between the collaborative module and the multi-criteria techniques is carried out with a search algorithm. The spectral occupancy data studied correspond to a GSM frequency band, obtained from previous measurements organized into power matrixes.

The research work is organized and presented into three section. The section 2 describes the methodology used to establish the input variables, the description and the functions of the collaborative model, the decision-making models and the performance metrics. The section 3 presents the results obtained and their respective comparative analysis, the multi-criteria techniques and the collaborative structure. Finally, the last section presents a set of conclusions on the overall work.

2 Methods

In order to perform a decision-making analysis in a collaborative environment, the methodology is structured in four stages. The first stage consists on establishing the information that feeds the general model which includes the input variables based on real measurements for the GSM frequency band (uplink). The second stage defines the collaborative model. The block diagrams presented in this section identifies the input-output relationship. A general example is discussed on how the proposed implementation works. The third stage describes the mathematical foundation behind multi-criteria models. In the fourth stage, the performance metrics for model quantification are analyzed.

2.1 Input variables

Power measurements in the GSM frequency band are used as input variables to carry out the analysis. The corresponding amount of information is shown in Table 1. The rows represent time in seconds and the columns represent the frequency channels. The sampling time for data capture was 290 ms.

The measurements require pre-processing to characterize the traffic level as High (few spectral opportunities) and Low (many spectral opportunities). Additionally, the type of model to be implemented makes it necessary to identify a data group that can train the models and another data group for validation. The matrix chosen for training allows setting the initial parameters of the algorithms and is then used for collaborative analysis. The assessment matrix is used to obtain the results of the assessment metrics of the implemented algorithms.

Based on the previous statements, two databases are used. One is used for training while the other one is used for assessment. Each database is classified into two traffic levels: High and Low. In total, there are 551 frequency channels, for 1 hour of training and 10 minutes for assessment. The size and classification are described in Table 2.

Table 1 Captured data

Frequency band	Quantity of data captured		
	Rows	Columns	Total data
GSM	1.145.700	551	631.280.700

Table 2 Selected data

Frequency band	Traffic	Traffic Level	Rows	Columns
GSM	Evaluation	HT: High	1800	551
		LT: Low		
	Training	HT:High	10800	551
		LT: Low		

2.2 Collaborative model

The structure of the collaborative model consists on sectioning the training matrix according to the established number of users. The following sections include a detailed description of the strategy.

2.2.1 Operation of the collaborative model

The input and output diagram of the collaborative model is presented in Fig. 1. It has three input parameters (the specific description of each module is shown in Fig. 8) and three output variables. The logic of the algorithm is based on taking the training matrix (input data) and segment it according to the inputs User Relations and Number of User. The outputs of the model are the segmented power matrix for training, the total number of users in which the matrix was sectioned (User Full) and the users that will participate in the training (User Simulation).

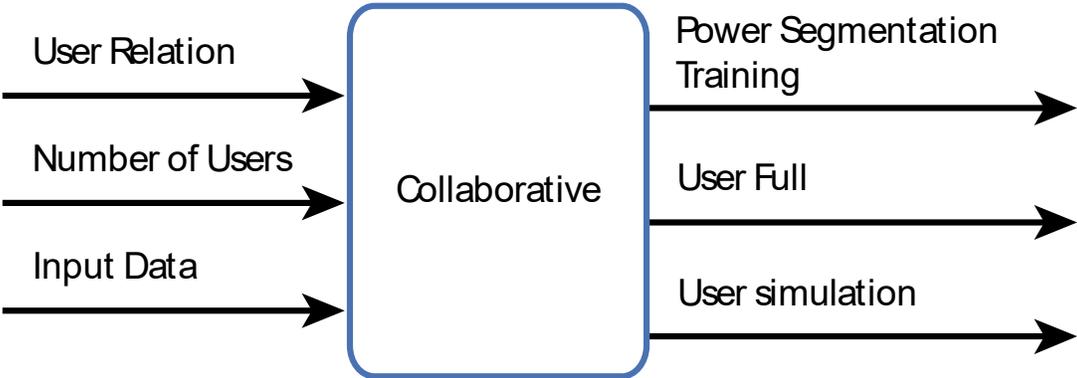


Fig. 1 Inputs and outputs collaborative model

A particular description of the model operation is presented in Fig. 2. The input matrix (Input Data) is received and split into submatrices (Number of User). Each submatrix

corresponds to the information that characterizes a user. Therefore, the number of submatrices corresponds to the number of users adjusted to the model input, for the model proposed in Fig. 2 the number of users adjusted corresponds to four (Number of Users = 4). After the separation process into submatrices, the amount of information to be shared in the training phase is determined (Segmentation Training) according to the collaboration level and the number of users or submatrices. According to Fig. 2 a collaboration level of 25% (User Relation = 25%) corresponds to a training process based in the information of a single user.

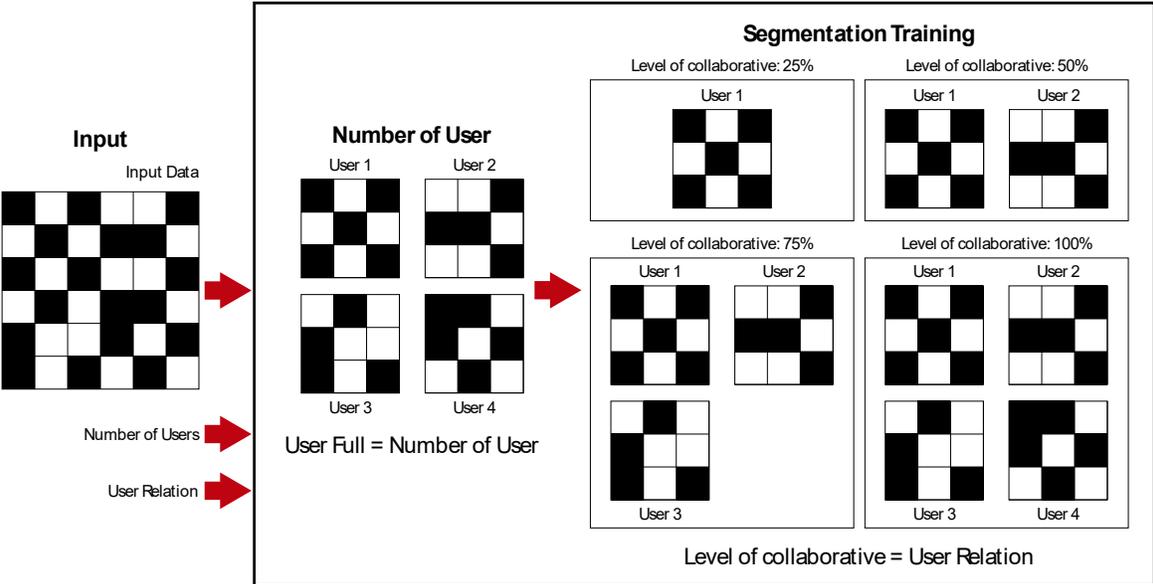


Fig. 2 Particular description of the collaborative model

For better understanding of the strategy, two examples are presented. In contrast with the case described in Fig. 2, these two scenarios are more specific since they involve all the adjustments that must be parameterized in the collaborative model. The Fig. 3 corresponds to a binary availability matrix (Input Data) with 36 data, analog to a power matrix. Each column represents a channel and each row represents time, where a value of '1' represents an available channel and a value of '0' represents an unavailable channel.

		Channels					
Time		1	1	0	1	0	0
		1	1	1	1	1	1
		0	1	0	0	0	1
		0	1	0	1	0	0
		1	0	0	1	1	0
		1	1	1	0	1	1

Fig. 3 Availability matrix

The availability matrix must be adjusted according to the user characteristics. The adjustments carried out for each scenario are presented in Table 3 and Table 4. For both cases, the availability matrix is sectioned into six users which is equivalent to six submatrices. Like the number of users, the User percentage variable is a randomly selected value, 50% for case 1 and 67% for case 2, this parameter indicates the percentage of users that will be part of the training, equivalent to a level of 50% collaboration (case 1) and 67% (case 2), therefore, if six is the total number of users (100%), 50% corresponds to training based on the information of three users, and the 67% corresponds to a training based on the information of four users. This percentage is an adjustable parameter that varies between 10% and 100% depending on the case of study. The collaborative model is programmed to adapt itself to any input parameter. For instance, if the collaboration level is adjusted during a training process based on the information of a non-integer number of users, then the model takes the closest integer. The variations in the model for the variables Division and Segmentation are described in the individual analysis of each study case. For more information on all the input variables, see Table 5.

Table 3 Example of a collaborative model adjustment - Case study 1

Input data	Disponibility matrix	
Number of Users	6	
User relation	Division	Row
	User percentage	50%
	Segmentation	Random

Table 4 Example of a collaborative model adjustment - Case study 2

Input data	Disponibility matrix	
Number of Users	6	
User relation	Division	Column
	User percentage	67%
	Segmentation	Continuous

Case 1: According to the information presented in Table 3, the case 1 sections the availability matrix into six users with row division. Since the number of users is less than ten and the segmentation is per row, the model takes the availability matrix and divides it into two columns (for users greater than ten see Table 5), then, it establishes in how many rows it must divide the availability matrix to be able to obtain a segmentation of six sub-matrices equivalent to six users, it must make a division into three rows. The Fig. 4 presents the availability matrix according to the number of users and division.

Only 50% of them are part of the training (variable that characterizes the collaboration levels), which corresponds to three users (User Simulation = 3) chosen randomly. The Fig. 5 illustrates the training matrix according to the adjustments described in Table 3.

		Channels						
Time	Row 1	User 1			User 2			
		1	1	0	1	0	0	
	1	1	1	1	1	1		
	Row 2	User 3			User 4			
		0	1	0	0	0	1	
	0	1	0	1	0	0		
Row 3	User 5			User 6				
	1	0	0	1	1	0		
1	1	1	0	1	1			
Column 1			Column 2					

Fig. 4 Availability matrix sectioned for six users with row division

		Channels						
Time	Row 1	User 1						
		1	1	0				
	1	1	1					
	Row 2				User 4			
					0	0	1	
	1	0	0	1	0	0		
Row 3	User 5							
	1	0	0					
1	1	1						
Column 1			Column 2					

Fig. 5 Training matrix for SU, with 50% collaboration and random selection

Case 2: According to the information presented in Table 4, case 2 sections the availability matrix into 6 users with column division. Since the number of users is less than ten and the segmentation is per column, the model takes the availability matrix and divides it into two rows (for users greater than ten see Table 5), then, it establishes in how many columns it must divide the availability matrix to be able to obtain a segmentation of six submatrices equivalent to six users, it must make a division into three columns. The Fig. 6 shows the availability matrix according to the number of users and division.

Out of the 6 users (Fig. 6) only 67% of them will be included in the training phase (variable that characterizes the collaboration levels), which corresponds to 4 users (User Simulation = 4) selected continuously. Fig. 7 presents the final training matrix according to the adjustments of Table 4.

		Channels					
		User 1		User 2		User 3	
Time	Row 1	1	1	0	1	0	0
		1	1	1	1	1	1
		0	1	0	0	0	1
	Row 2	User 4		User 5		User 6	
		0	1	0	1	0	0
		1	0	0	1	1	0
		1	1	1	0	1	1
		Column 1	Column 2	Column 3			

Fig. 6 Availability matrix sectioned for six users with column division

		Channels							
		User 1		User 2		User 3			
Time		1	1	0	1	0	0	Row 1	
		1	1	1	1	1	1		
		0	1	0	0	0	1		
			User 4						Row 2
			0	1					
			1	0					
			1	1					
		Column 1		Column 2		Column 3			

Fig. 7 Training for four secondary users, with 67% collaboration and continuous selection

2.2.2 Functions of the collaborative model

In the previous section the operation of the collaborative module was described, in general terms the input variables were mentioned, and through two case studies, the methodology implemented to segment the availability matrix. In this section of the article we present the specific description of the collaborative algorithm, the programming structure, the implemented functions, and the input and output variables.

The collaborative algorithm segments the matrix through three functions, the Fig. 8 presents the specific block diagram of the collaborative model. The blocks where the input and output signals converge correspond to the functions of the algorithm. The first function is called “User Division” is in charge of dividing the matrix according to the adjustments of the number of users (Number of user and User Full). The second block is comprised of two functions: User Zone Continuous and User Zone Random. These functions are in charge of

selecting the block of users. The selection method is parameterized by the “Segmentation” variable. If the continuous selection method is chosen, the function “User Zone Continuous” is in charge of the selection. If the random method is chosen, then the “User Zone Random” function performs the selection. The following sections describe the characteristics and adjustments of each input and output variable of the implemented collaborative model.

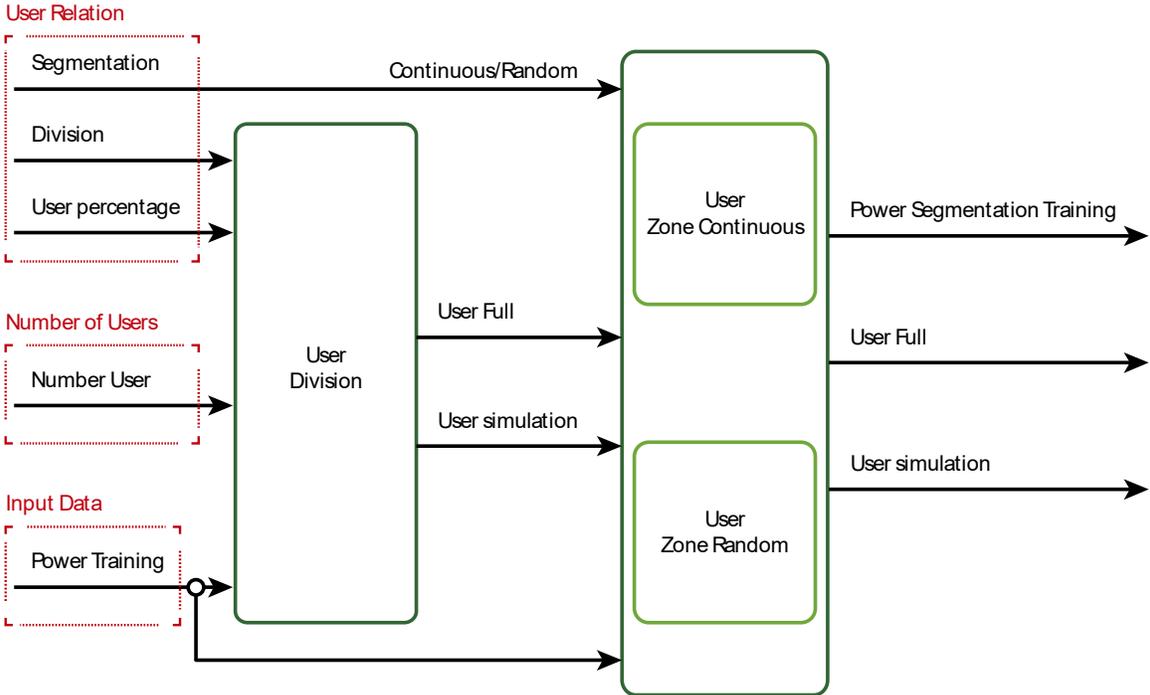


Fig. 8 Functions of the collaborative model

2.2.3 Input variable

The Fig. 8 shows the three sets of input variables: User Relation, Number User and Input Data. The description for each variable is presented in tables 5, 6 and 7 respectively.

2.2.4 Output variable

The Fig. 8 the algorithm has three output variables: Power Segmentation Training, User Full and User Simulation. The description of each variable show in Table 8.

Table 5 User relation

Variable	Element	Description
Segmentation	Random Zone	The percentage of users selected for simulation is chosen at random.
	Random Zone	The percentage of users selected for simulation is taken in an orderly manner, row-wise or column-wise.
Division	Column	If the number of users is greater than 10, the rows of the power matrix are divided into 10 equal parts and the columns are split into n parts until the number of users is completed. If the number of users is less than 10, the rows of the power matrix are divided into 2 equal parts and the columns are split into n parts until the number of users is completed.
	Row	If the number of users is greater than 10, the columns of the power matrix are divided into 10 equal parts and the rows are divided into n parts until the number of users is completed. If the number of users is less than 10, the columns of the power matrix are divided into 2 equal parts and the columns are split into n parts until the number of users is completed.
User percentage	10-100	Percentage of users participating for the training.

Table 6 Number of users

Variable	Element	Description
Number of users	1-1000 User	Number of users utilized to divide the power matrix for the training.

Table 7 Power matrix

Variable	Element	Description
Power Training	High	Traffic power matrix for the training
	Low	

Table 8 Output variables

Variable	Description
Power Segmentation Training	The segmented power matrix according to the number of users that participate for the training
User Full	Total number of users utilized to divide the power matrix
User Simulation	Number of users participative for the training

2.3 Decision-making models

The decision-making process is done separately from the collaborative model, however, although its design is external to the collaborative block, it requires the Power Segmentation Training output matrix to work. Next, the results of the collaborative model and the decision-making will be connected through a search algorithm (section 2.4).

To analyze the decision-making process, two MCDM techniques are implemented. The chosen strategies are: Feedback Fuzzy Analytical Hierarchical Process (FFAHP) [17, 28] and Simple Additive Weighting (SAW) [17, 27]. Furthermore, the analysis is carried out according to the class service: real-time (RT) and best effort (BE).

The decision-making analysis uses a module called “MCDM” in charge of assigning a score to various channels. The purpose is to establish channels with a higher probability of spectral opportunity. The Fig. 9 shows the input variables required to parameterize the module, as well as the output vectors of the block. The first output vector one contains the score allocated to each channel, while the second output vector contains the ranking of the channels in ascending order according to the score obtained (Ranking). The Table 9 presents the description of each of the input vector.

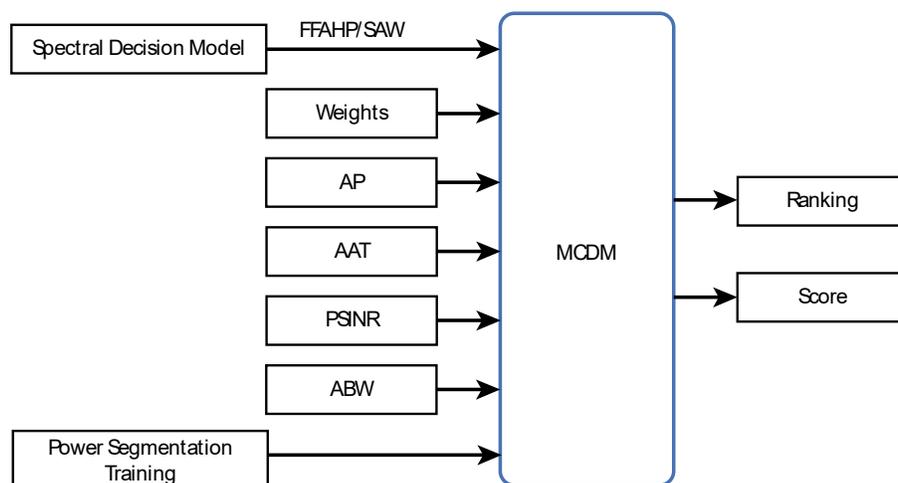


Fig. 9 Input and output variable of the MCDM module

Table 9 Number of users

	Average	Description
AP	Availability probability	Average of each column of the availability matrix
AAT	Average availability time	Average of some consecutives of the availability matrix
PSINR	Average SINR	Average of each column of the SINR matrix without including zeros
ABW	Average bandwidth	Average of each column of the bandwidth matrix

2.3.1 FFAHP

The FFAHP algorithm (Feedback FAHP) proposes the feedback of the information from previous assessments based on the FAHP method [28]. The FAHP algorithm uses fuzzy logic as a tool which is particularly adequate to make decisions in scenarios where the inputs are often uncertain or inaccurate. In essence, the FAHP algorithm uses the same methodology of the AHP algorithm [17]. However, fuzzy logic supports in handling the subjectivity and uncertainty generated during the assessment process [28]. After normalization, the FAHP algorithm states that the weight vector is given by (1).

In methods based in the AHP algorithm, judgment matrixes must be built, which performs comparative assessments that define the level of relative importance between each possible combination of the criteria, sub criteria and alternatives, independently. For instance, the RT and BE applications are criteria based on different approaches. In RT, the sub-criteria with the highest priorities are those which reduce the delay. For BE, the sub-criteria with the highest priority are those which increase the data rate, such as BW and SINR.

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

If the algorithm is using the RT application, the score for each channel is computed using (2), while (3) is used for BE applications. The coefficients of each of the equations are taken from [28]. The Table 9 presents the description of each variable indicated in the equations.

$$Score_{RT} = 0.3593(AP) + 0.2966(AAT) + 0.1970(PSINR) + 0.1471(ABW) \quad (2)$$

$$Score_{BE} = 0.1607(AP) + 0.1523(AAT) + 0.3949(PSINR) + 0.2921(ABW) \quad (3)$$

2.3.2 SAW

This algorithm develops a decision making matrix comprised of criteria and alternatives. The spectral opportunity with the highest score is chosen, where $r_{i,j}$ belongs to the matrix and the sum of weights is equal to 1 (4) [27, 30, 31].

$$u_i = \sum_{j=1}^M \omega_j r_{i,j} \quad \forall i \in 1, \dots, N \quad (4)$$

For each intersection of the matrix, the algorithm assigns a weight ((5) and (6)) his enables to establish a score for each assessed spectral opportunity and deliver the ranking of the alternatives. The spectral opportunity with the highest score is chosen. The coefficients of each of the equations are taken [28].

$$Score_{RT} = 0.3985(AP) + 0.3005(AAT) + 0.0989(PSINR) + 0.2021(ABW) \quad (5)$$

$$Score_{BE} = 0.2078(AP) + 0.3989(AAT) + 0.1020(PSINR) + 0.2913(ABW) \quad (6)$$

2.4 Performance metrics

The connection between the collaborative module and multicriteria techniques is carried

out through a search algorithm, as shown in Fig. 10. The output variables of the “Collaborative” and “MCDM” modules correspond to the inputs of the “Search Algorithm”. Additionally, this module requires two additional parameters for adjustment, the Time and Time Range variables. The output of the search algorithm corresponds the assessment metrics of failed handoff.

2.4.1 Search algorithm

The search algorithm is in charge of carrying out column-wise jumps (frequencies) in the availability matrix according to the position vector delivered by the MCDM module. The algorithm jumps from one column to another until it finds a value of ‘1’. Said vector is equivalent to an available frequency and each column jump is stored. When column-wise jumps are performed, if the algorithm finds a value of ‘1’, it automatically jumps to the following row of the availability matrix within the same column. It is noteworthy to mention that each row represents a time instant. The stop condition of the search algorithm is defined by the variable Time (transmission time selected by the user). Row-based jumps are performed until the established transmission time is completed. Column-wise jumps, row-wise jumps and time are stored into a vector to subsequently quantify the failed handoff rates.

2.4.2 Failed handoff

A spectral handoff (SH) can be defined as the process where a SU changes its operation frequency, when the conditions of a channel are degraded or when a PU asks for service, given that that the secondary user is using a licensed band [26]. The SH concept of CR differs from traditional wireless network mechanisms in the sense that there are two types

of users with different priorities [2]. A failed handoff corresponds to the number of unsuccessful handoffs, meaning that the SU cannot materialize handoff since it finds that the respective spectral opportunity is occupied [2].

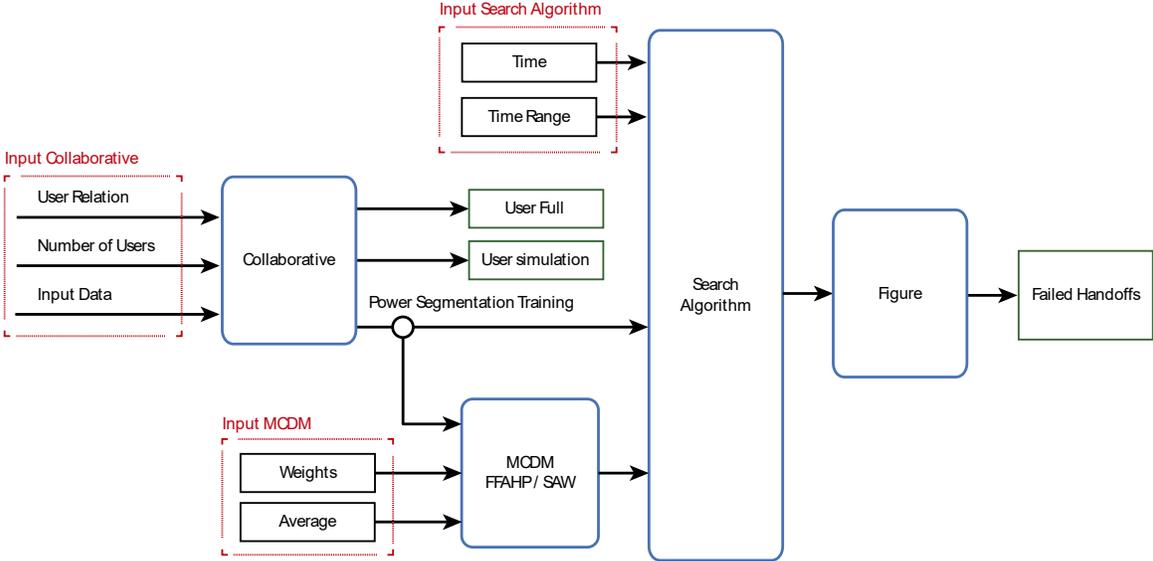


Fig. 10 Block diagram of the collaborative model, multicriteria and search algorithm

3 Results and Discussion

The results are presented through two analyses. The first analyzes the number of failed handoffs, for each of the five collaboration levels (10%, 20%, 50%, 80% and 100%), according to the decision-making model, the class of service (RT, BE) and the traffic level (HT, LT). The second quantifies the collaboration level for the number failed handoffs according to the 100% of collaboration. Finally, the comparative analysis determine how much information is required to be shared.

3.1 Number of failed handoffs

The figures 11 to 14 show the number of failed handoffs for a transmission time of nine minutes using FFAHP and SAW as multicriteria technique, the analysis is carried out according to the class service: real time (RT), best effort (BE), and according to the level of

traffic: High (HT), Low (LT).

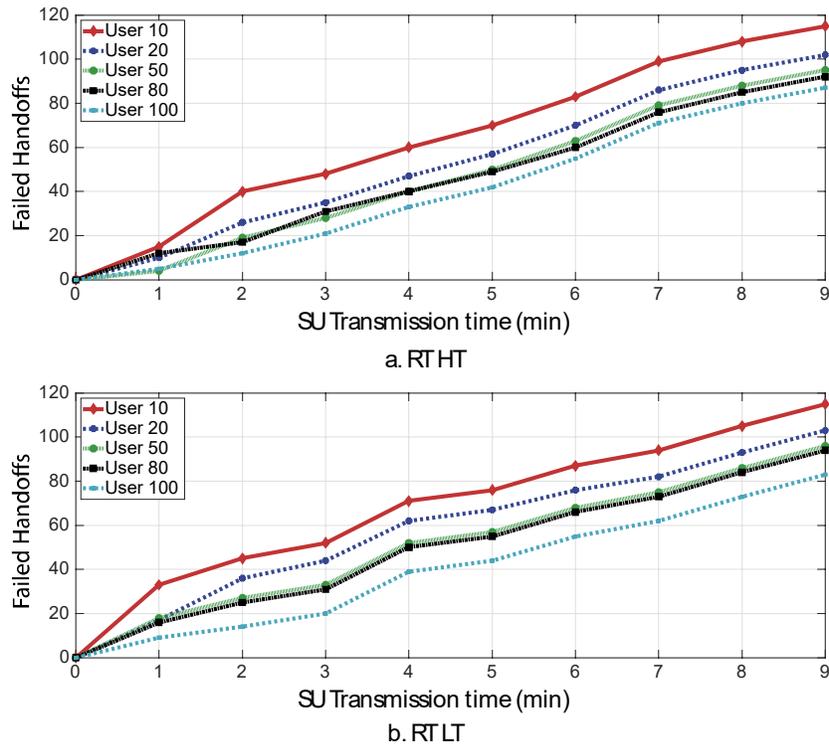


Fig. 11 Failed handoffs for FFAHP RT

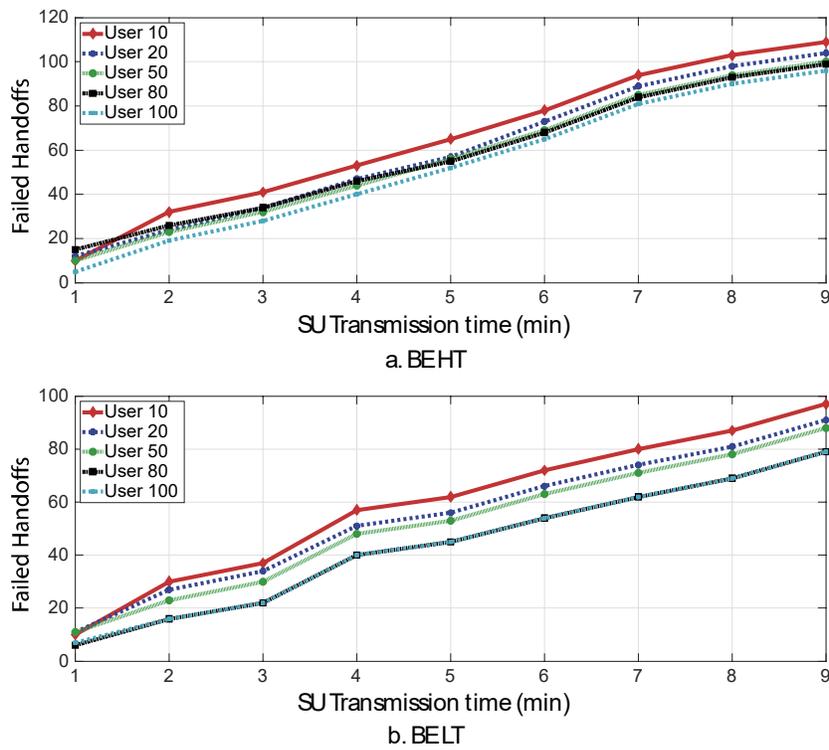
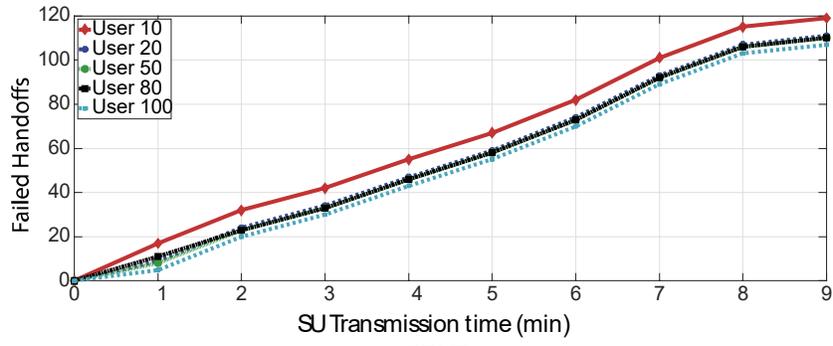
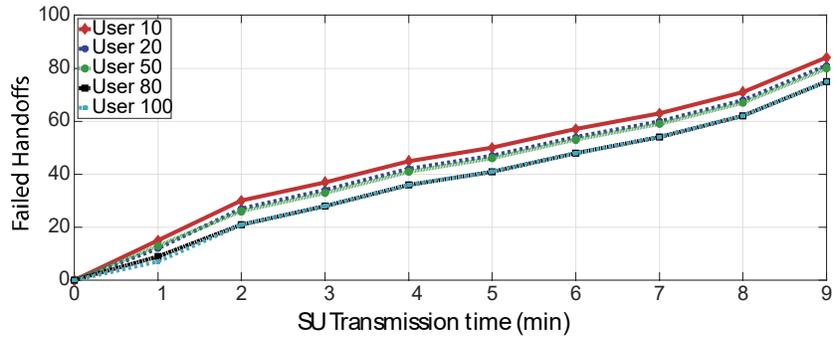


Fig. 12 Failed handoffs for FFAHP BE

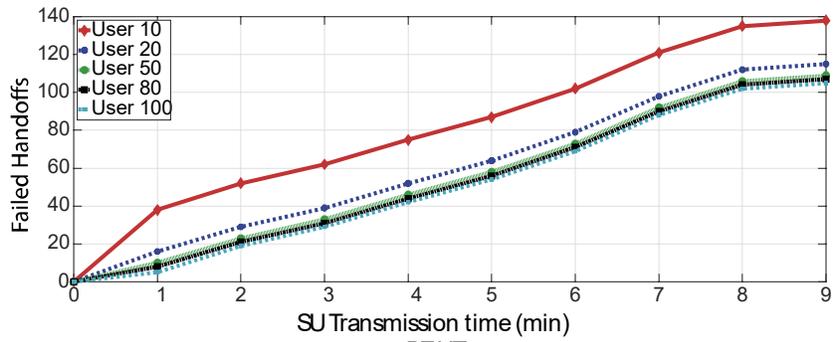


a. RT HT

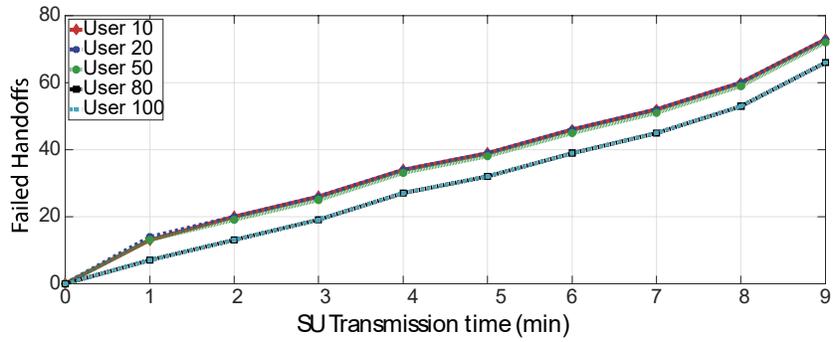


b. RT LT

Fig. 13 Failed handoffs for SAW RT



a. BEHT



b. BELT

Fig. 14 Failed handoffs for SAW BE

The results reveal that both multicriteria techniques show an equivalent tendency for all five levels of collaboration. The trend of the number of handoffs is equivalent for all five levels of collaboration. 100% collaboration leads to the lowest levels while 10% collaboration leads to the highest levels. The other collaboration levels can be found between these two limits.

3.2 Percentage analysis of the collaboration

To establish a collaboration criterion in terms of the number of failed handoffs, a percentage-based analysis is carried. The objective is to use 100% of the shared information as the base criterion, this level has the lowest indicators.

The Fig. 15 show the relation for the number of failed handoffs with FFAHP with real time (RT) service. The increments rates for each collaboration level are presented in percentage form. For high traffic (HT), the minimum number of failed handoffs (min FFAHP) was 87. The average rate of corresponds to 16.1% (14 failed handoffs), which corresponds to a collaboration level between 20% and 50%. For low traffic (LT), the minimum number of failed handoffs (min FFAHP) was 83. The average increase rate corresponds to 22.9% (19 failed handoffs), which corresponds to a collaboration level between 20% and 50%.

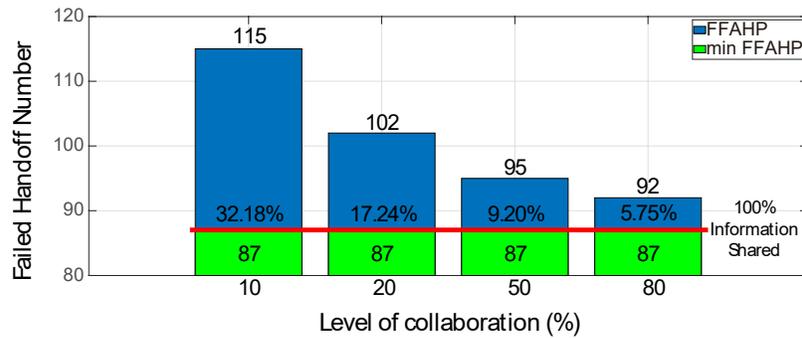
The Fig. 16 show the relation for the number of failed handoffs with FFAHP with better effort (BE) service. The increments rates for each collaboration level are presented in percentage form. For high traffic (HT), the minimum number of failed handoffs (min FFAHP) was 2286. The average rate of corresponds to 11.5% (263 failed handoffs), which corresponds to a collaboration level between 10% and 20%. For low traffic (LT), the minimum number of failed handoffs (min FFAHP) was 906. The average increase rate

corresponds to 15.1% (137 failed handoffs), which corresponds to a collaboration level between 10% and 20%.

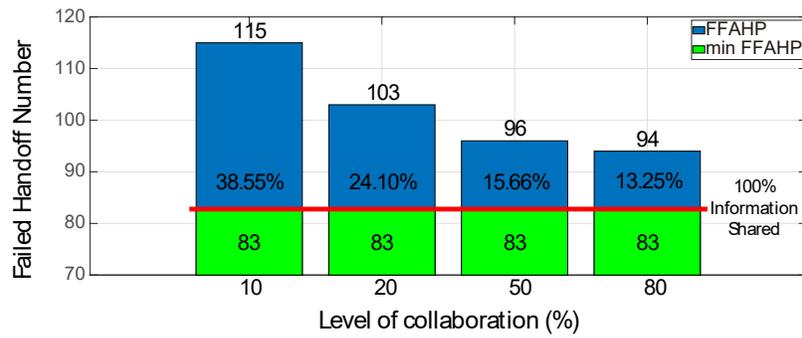
The Fig. 17 show the relation for the number of failed handoffs with SAW with real time (RT) service. The increments rates for each collaboration level are presented in percentage form. For high traffic (HT), the minimum number of failed handoffs (min SAW) was 107. The average rate of corresponds to 5.1% (6 failed handoffs), which corresponds to a collaboration level between 20% and 50%. For low traffic (LT), the minimum number of failed handoffs (min SAW) was 75. The average increase rate corresponds to 6.7% (5 failed handoffs), which corresponds to a collaboration level between 20% and 50%.

The Fig. 18 show the relation for the number of failed handoffs with SAW with better effort (BE) service. The increments rates for each collaboration level are presented in percentage form. For high traffic (HT), the minimum number of failed handoffs (min SAW) was 105. The average rate of corresponds to 11.7% (12 failed handoffs), which corresponds to a collaboration level between 10% and 20%. For low traffic (LT), the minimum number of failed handoffs (min SAW) was 66. The average increase rate corresponds to 7.6% (137 failed handoffs), which corresponds to a collaboration level between 50% and 80%.

Based on the percentage relations obtained, the level of information shared and the average increase rates, it is determined that, for a given the number of failed handoffs, the collaboration range that enables efficient results varies between 10% and 20%, where 20% of the shared information is considered the representative limit of the range. For better effort (BE), the range from 20% to 50% delivers the highest efficiency according to the average increase rates.

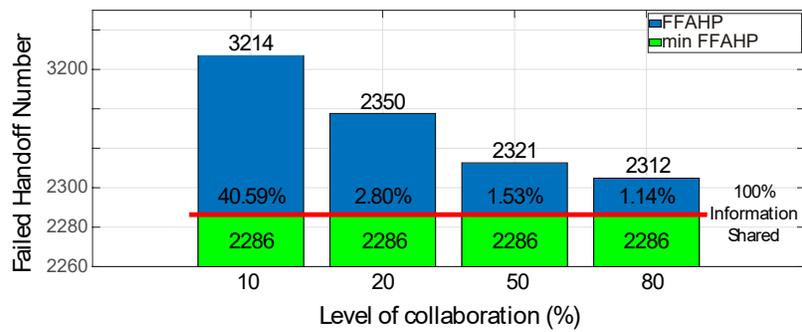


a. RT HT

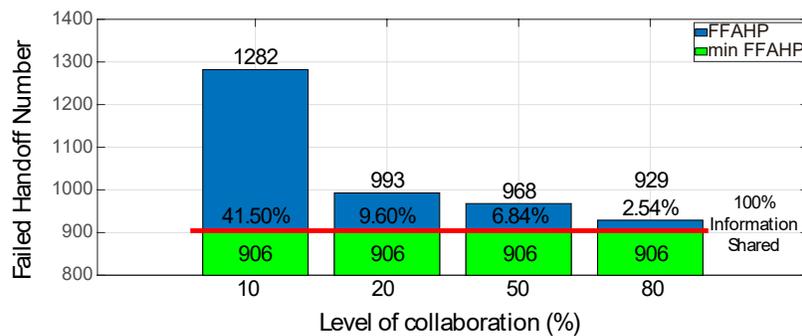


b. RT LT

Fig. 15 Failed handoffs for FFAHP with real time (RT) service

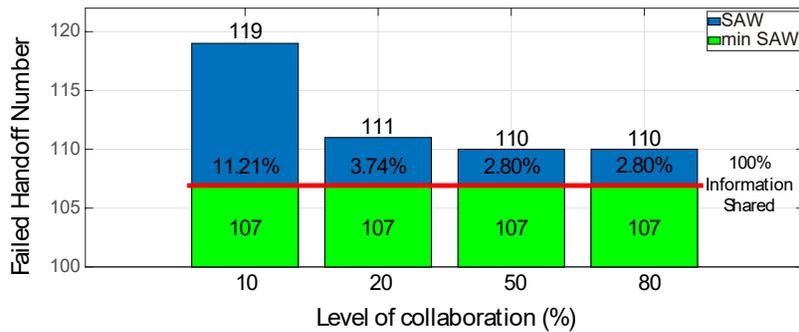


a. BE HT

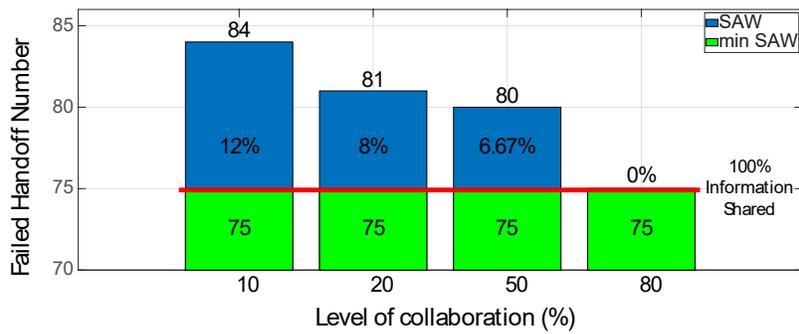


b. BE LT

Fig. 16 Failed handoffs for FFAHP with better effort (BE) service

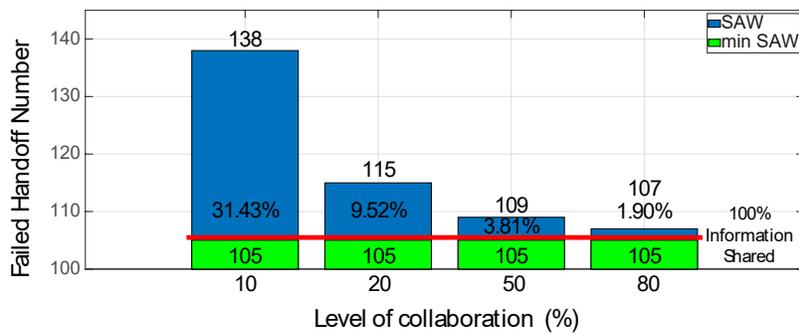


a. RT HT

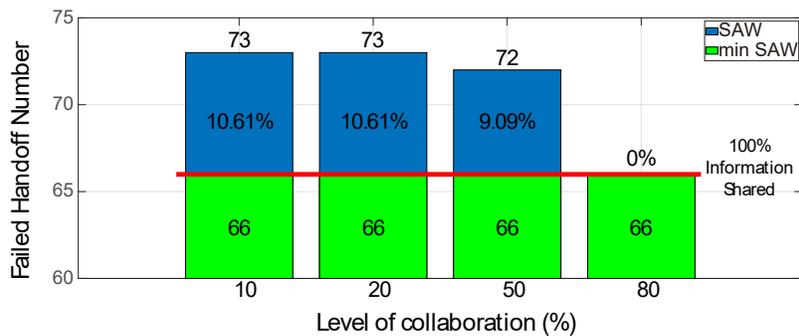


b. RT LT

Fig. 17 Failed handoffs for SAW with real time (RT) service



a. BE HT



b. BE LT

Fig. 18 Failed handoffs for SAW with better effort (BE) service

4 Conclusions

This work analyses the level of information that secondary users need to share to establish a proper decision-making process. The number of failed handoffs are assessed according to the segmentation structure with five percentages of collaboration (10%; 20%, 50%, 80% and 100%). The decision-making process is carried out through two multi-criteria techniques, that have shown excellent results which are widely used in these types of problems: Feedback Fuzzy, Analytical Hierarchical Process and Simple Additive Weighting. The analysis is developed in three stages: the first one is a collaborative model which divides the training matrix; the second one is a decision-making block that implements two multi-criteria techniques. Finally, the third stage consists on a search algorithm that quantifies the performance metrics. Used for the training process and validation of real power measurements, within the GSM frequency band commercial.

For both multi-criteria techniques (SAW and FFAHP) under two traffic levels (high and low) and two types of classes (BE and RT), two analysis criteria are implemented. The first one involves the total number of failed handoffs and the second one quantifies the collaboration level for the failed handoff rates according to the 100% of collaboration. For the criterion, the behaviors are proportional. Since these are cumulative metrics, the failed handoff rate grows according to the transmission time. The tendency of the number of failed handoffs is equivalent for all five percentages of collaboration analyzed. In the second criterion, based on the amount information shared and the average increase rates, the percentage of collaboration leads to efficient results between 20% and 50%.

List of Abbreviations

BE: Best effort

CR: Cognitive radio

CRN: Cognitive radio networks

FFAHP: Feedback Fuzzy Analytical Hierarchical Process

FIS: Fuzzy interference system

HT: High traffic

LT: Low traffic

MCDM: Multi-criteria decision-making

PU: Primary user

RT: Real-time

SAW: Simple Additive Weighting

SH: Spectral handoff

SINR: Signal plus interference noise ratio

SU: Secondary user

Declarations

Availability of data and materials

Please contact the authors for data requests

Competing Interest

The authors declare that they have no competing interests

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Authors Contribution

DG, CH, and ER declare that they contributed to the manuscript. All authors prepared, read and approved the final manuscript.

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Figure Title and Legend Section

Figure 1 Inputs and outputs collaborative model

Figure 2 Particular description of the collaborative model

Figure 3 Availability matrix

Figure 4 Availability matrix sectioned for six users with row division

Figure 5 Training matrix for SU, with 50% collaboration and random selection

Figure 6 Availability matrix sectioned for six users with column division

Figure 7 Training for four secondary users, with 67% collaboration and continuous selection

Figure 8 Functions of the collaborative model

Figure 9 Input and output variable of the MCDM module

Figure 10 Block diagram of the collaborative model, multicriteria and search algorithm

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Figure 17 Failed handoffs for SAW with real time (RT) service

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Table 1 Captured data

Table 2 Selected data

Table 3 Example of a collaborative model adjustment - Case study 1

Table 4 Example of a collaborative model adjustment - Case study 2

Table 5 User relation

Table 6 Number of users

Table 7 Power matrix

Table 8 Output variables

Table 9 Number of users

Figures

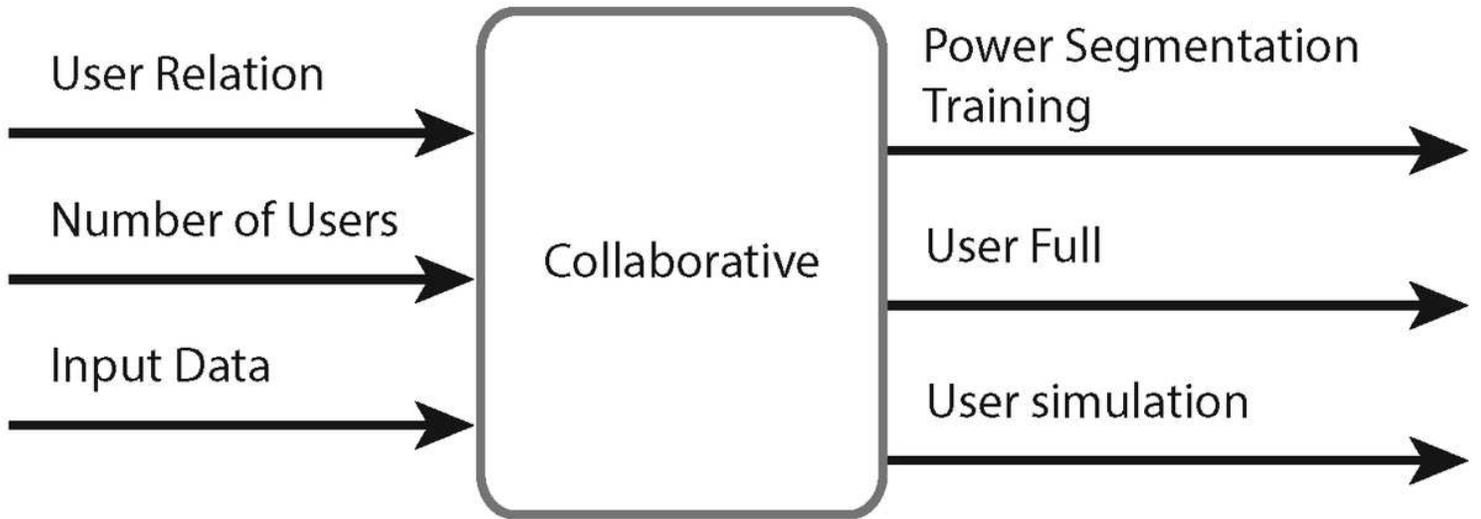


Figure 1

Inputs and outputs collaborative model

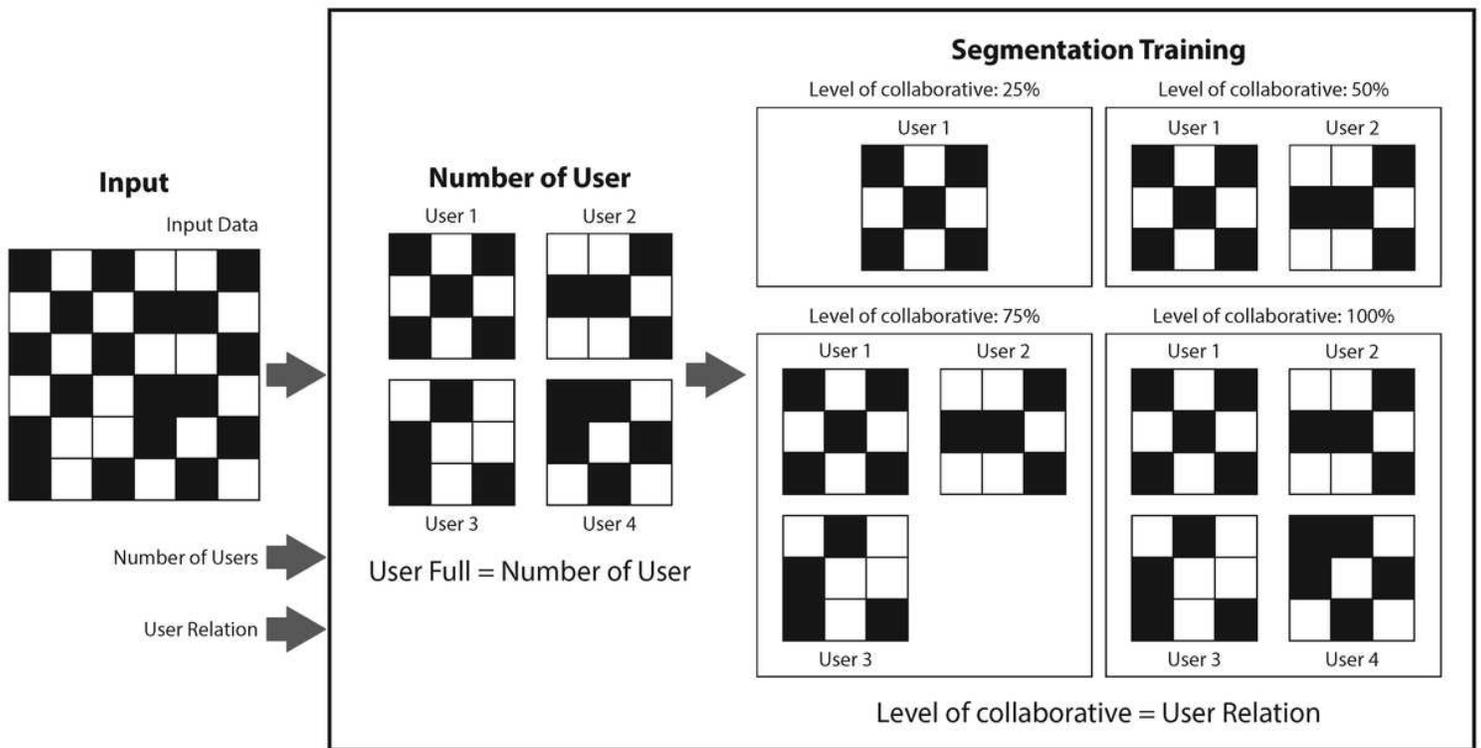


Figure 2

Particular description of the collaborative model

		Channels					
Time		1	1	0	1	0	0
		1	1	1	1	1	1
		0	1	0	0	0	1
		0	1	0	1	0	0
		1	0	0	1	1	0
		1	1	1	0	1	1

Figure 3

Availability matrix

		Channels						
Time	User 1			User 2				
	1	1	0	1	0	0	Row 1	
	1	1	1	1	1	1		
	User 3			User 4				
	0	1	0	0	0	1	Row 2	
	0	1	0	1	0	0		
	User 5			User 6				
	1	0	0	1	1	0	Row 3	
	1	1	1	0	1	1		
	Column 1			Column 2				

Figure 4

Availability matrix sectioned for six users with row division

		Channels			
Time	User 1				Row 1
	1	1	0		
	1	1	1		
	User 4				Row 2
	0	0	1		
	1	0	0		
User 5				Row 3	
1	0	0			
1	1	1			
		Column 1	Column 2		

Figure 5

Training matrix for SU, with 50% collaboration and random selection

		Channels						
Time		User 1		User 2		User 3		Row 1
		1	1	0	1	0	0	
		1	1	1	1	1	1	
		0	1	0	0	0	1	
		User 4		User 5		User 6		Row 2
		0	1	0	1	0	0	
		1	0	0	1	1	0	
		1	1	1	0	1	1	
		Column1	Column2	Column3				

Figure 6

Availability matrix sectioned for six users with column division

		Channels								
Time		User 1		User 2		User 3		Row 1		
		1	1	0	1	0	0			
		1	1	1	1	1	1			
		0	1	0	0	0	1			
		User 4								Row 2
		0	1							
		1	0							
	1	1								
		Column1	Column2		Column3					

Figure 7

Training for four secondary users, with 67% collaboration and continuous selection

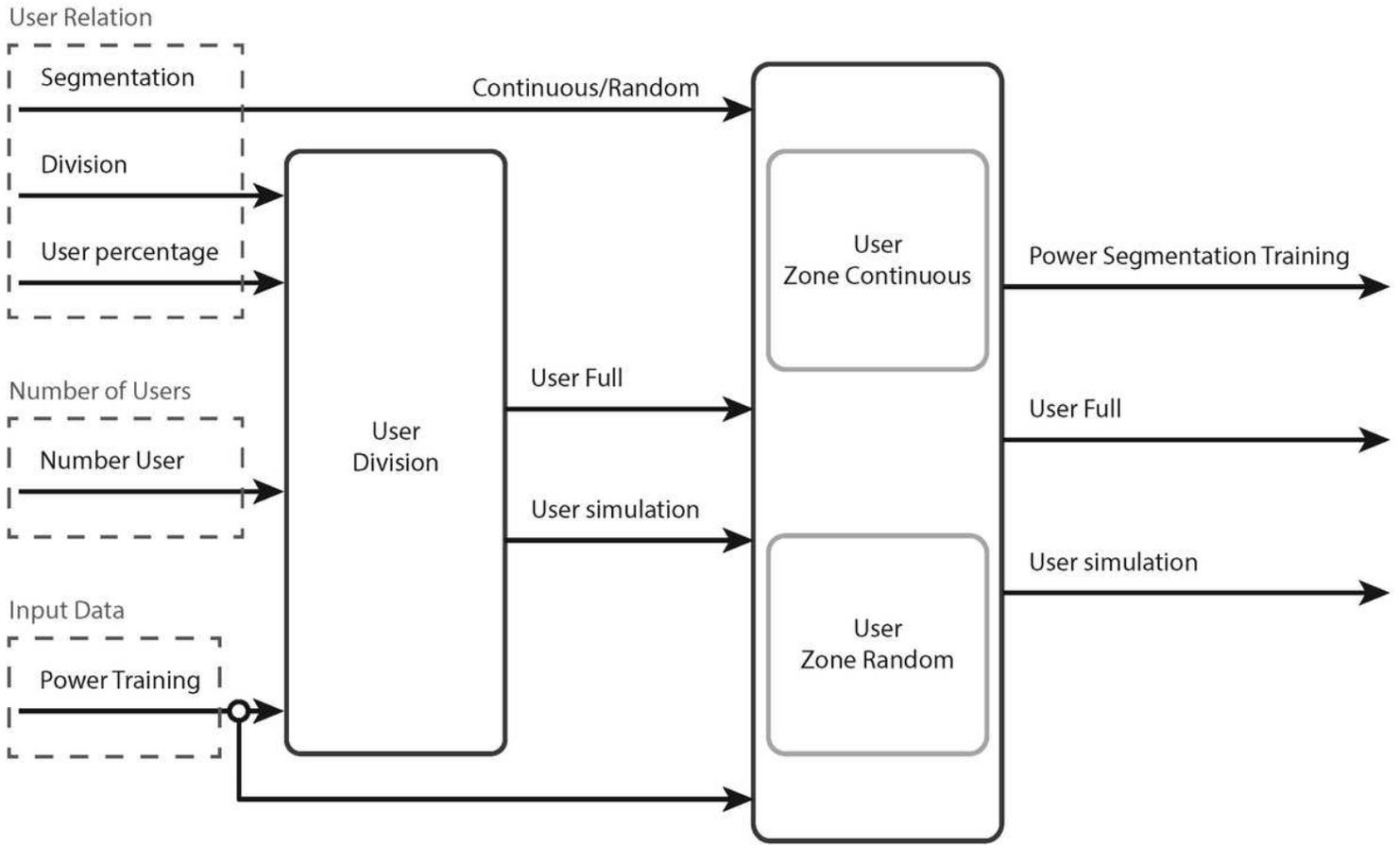


Figure 8

Functions of the collaborative model

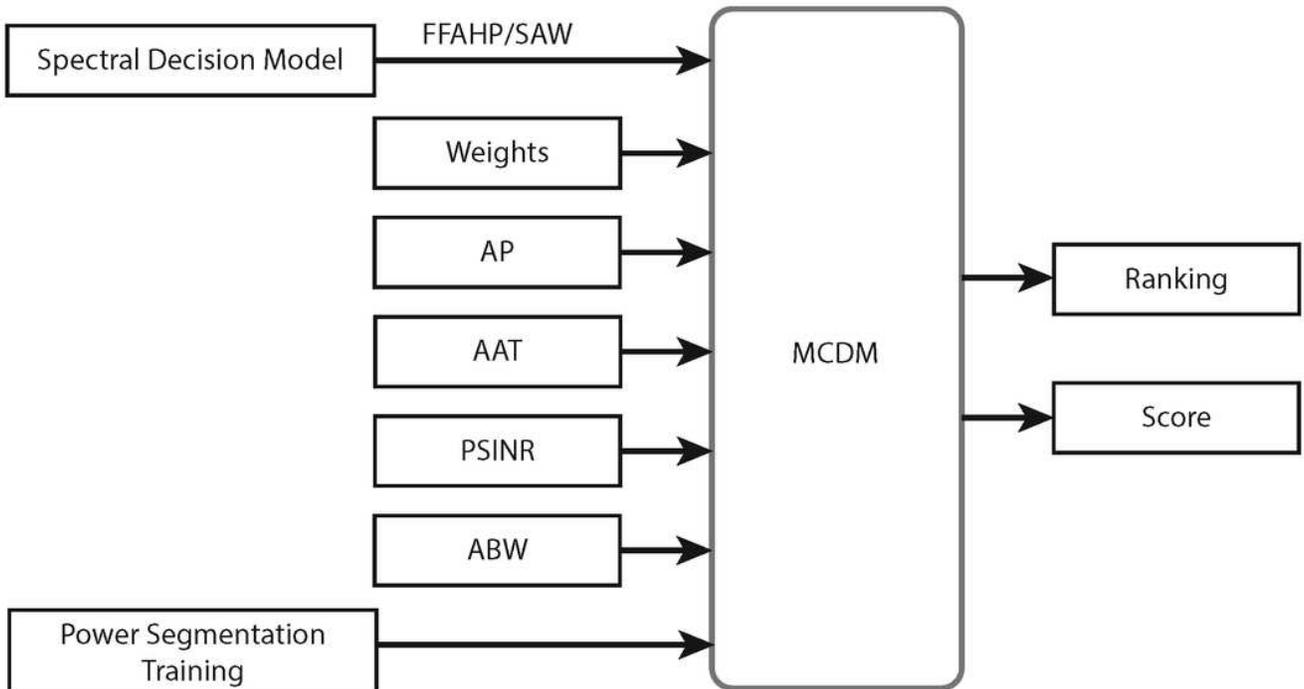


Figure 9

Input and output variable of the MCDM module

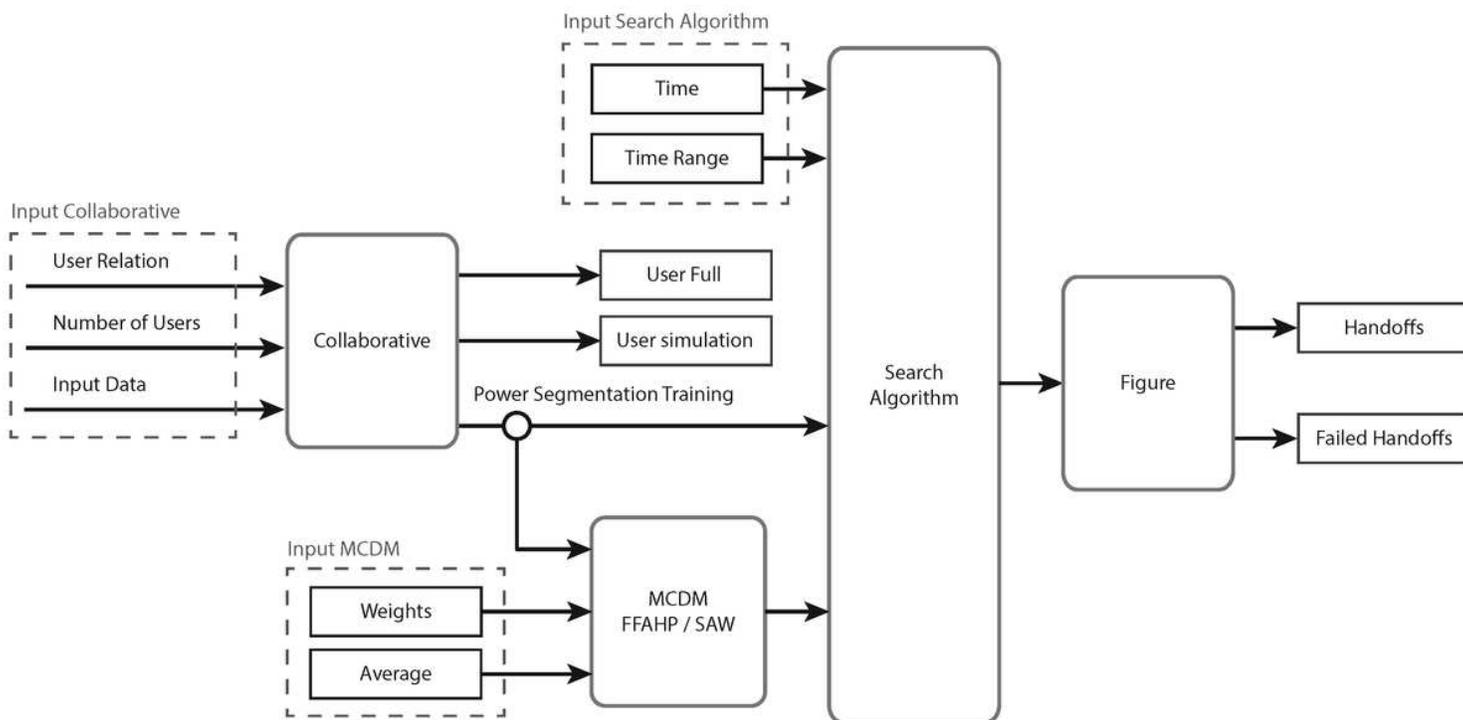
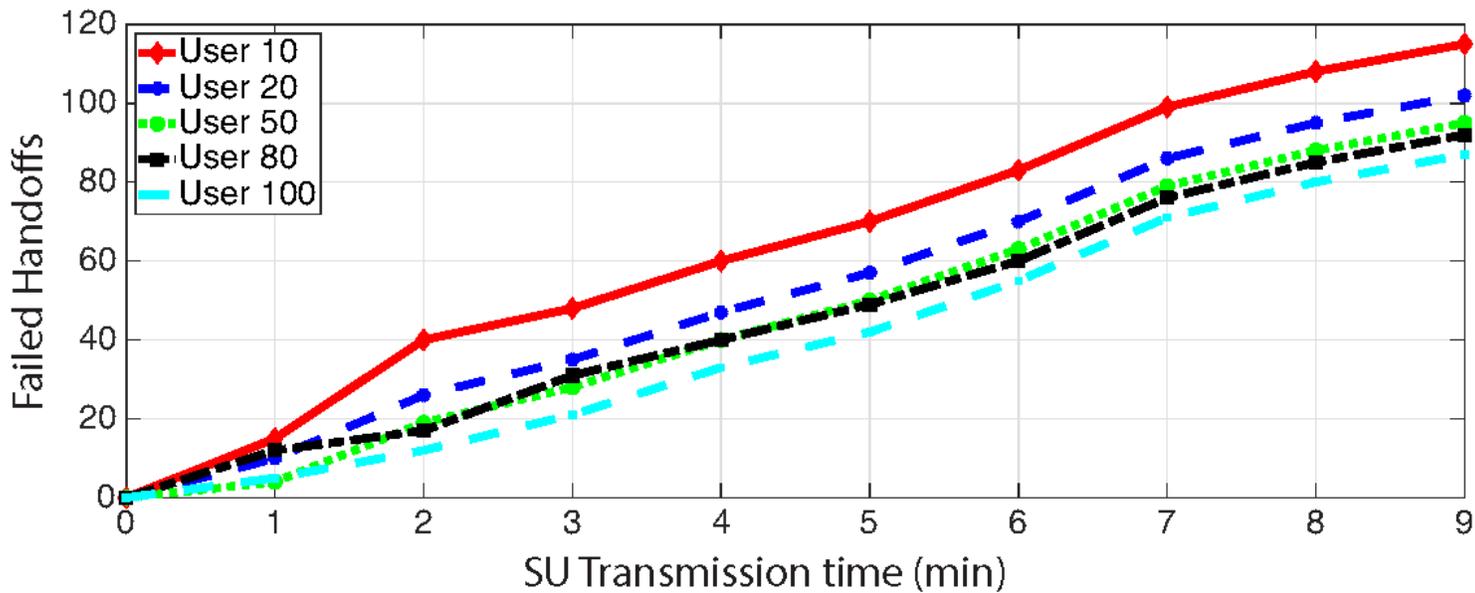
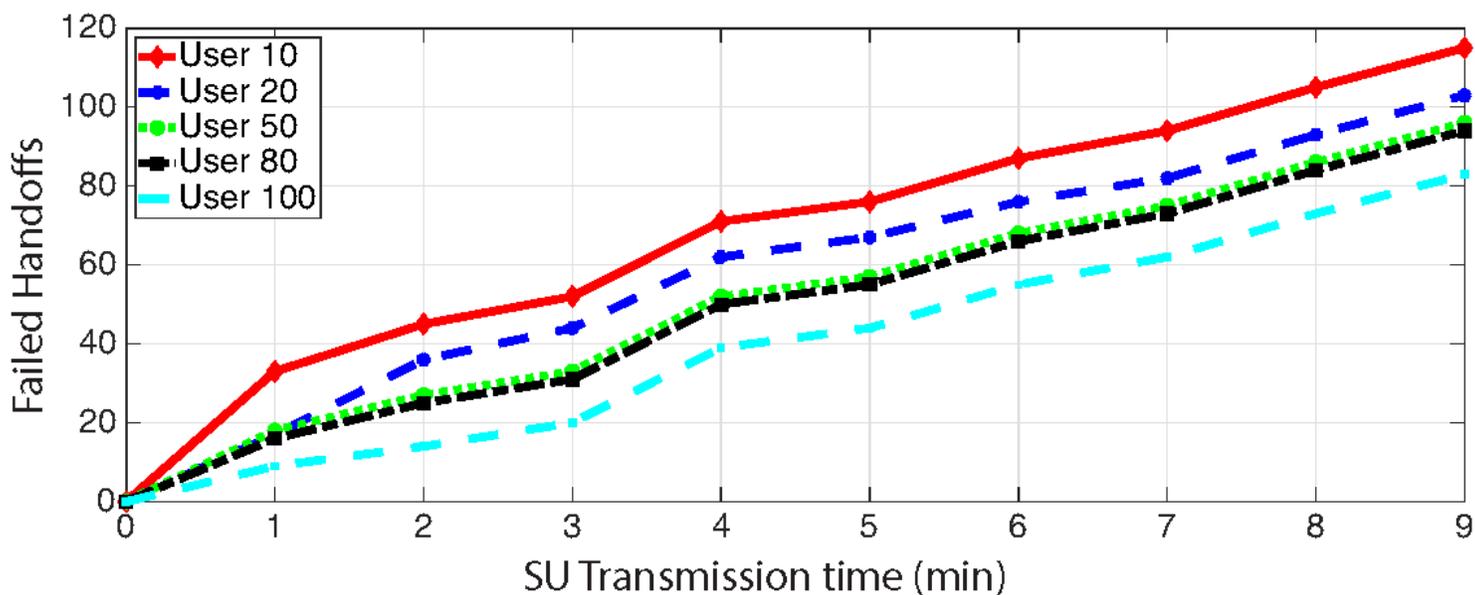


Figure 10

Block diagram of the collaborative model, multicriteria and search algorithm



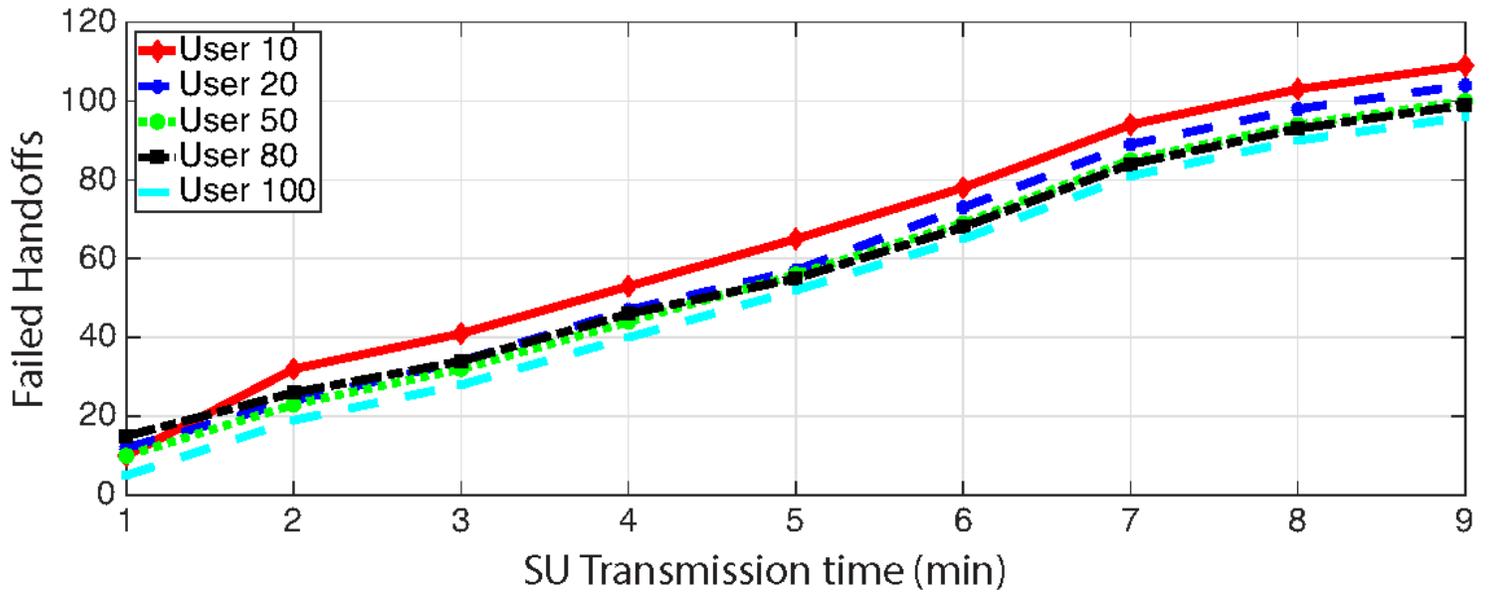
a. RT HT



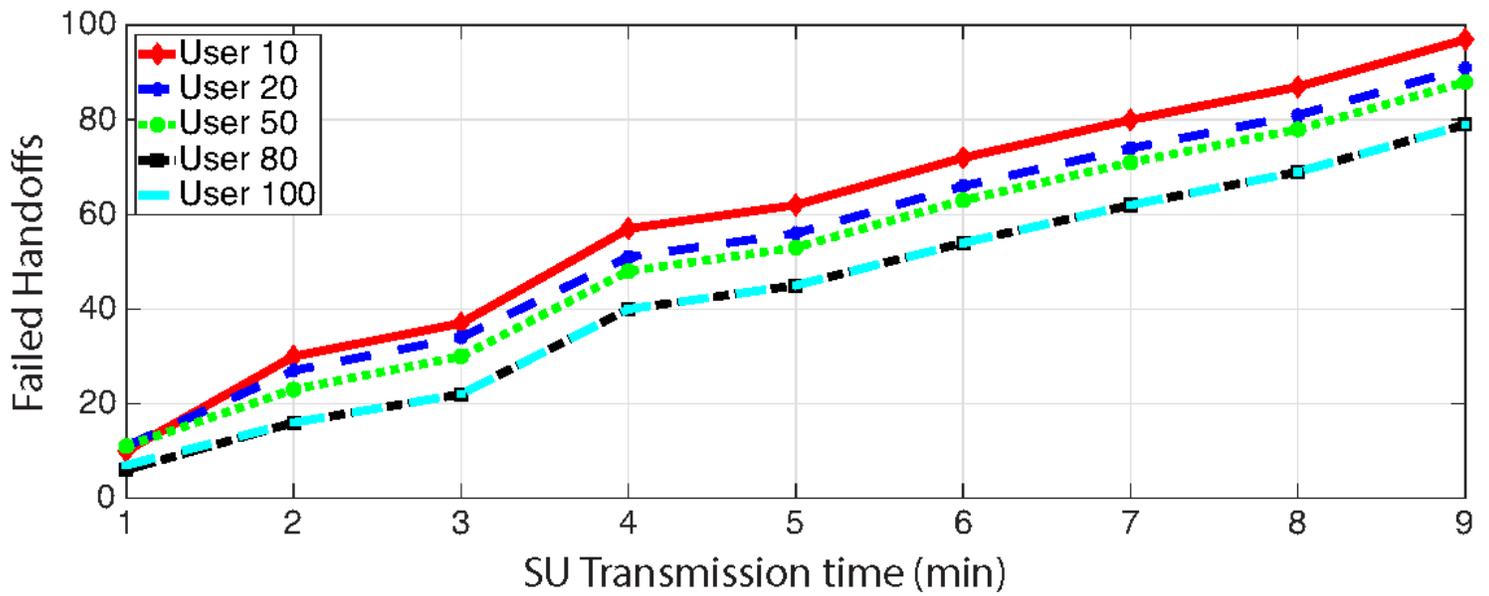
b. RT LT

Figure 11

Failed handoffs for FFAHP RT



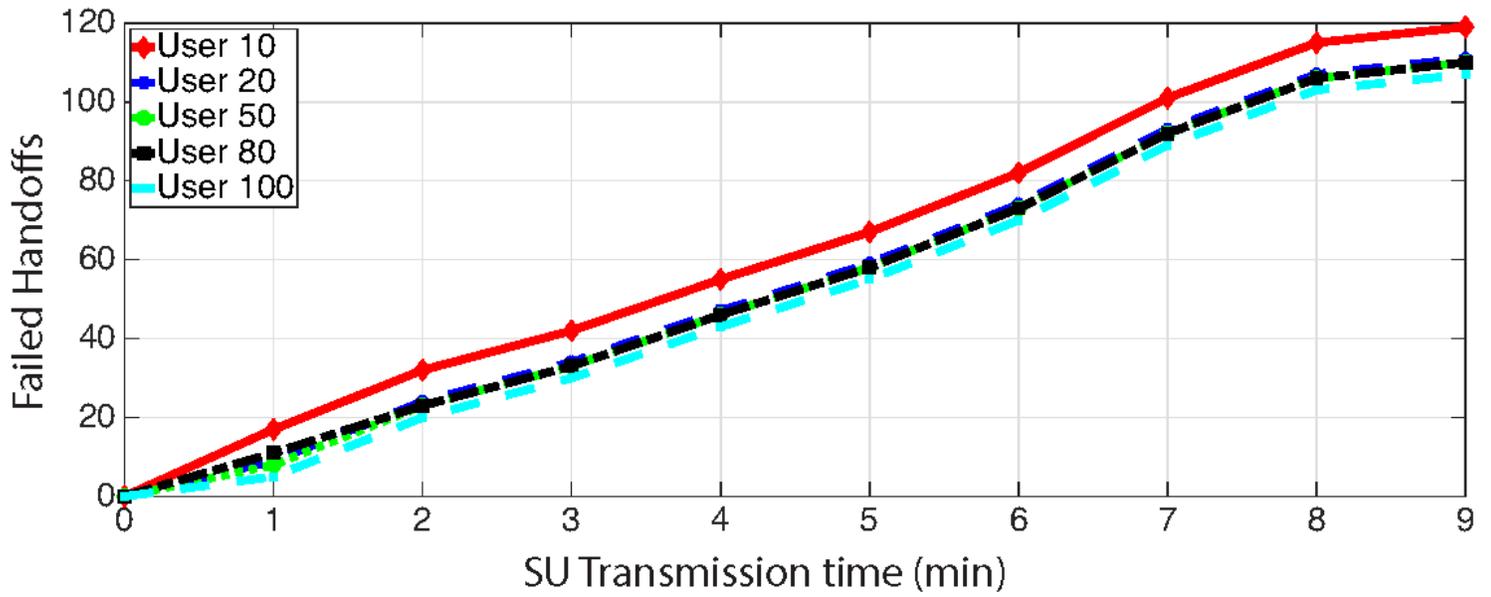
a. BE HT



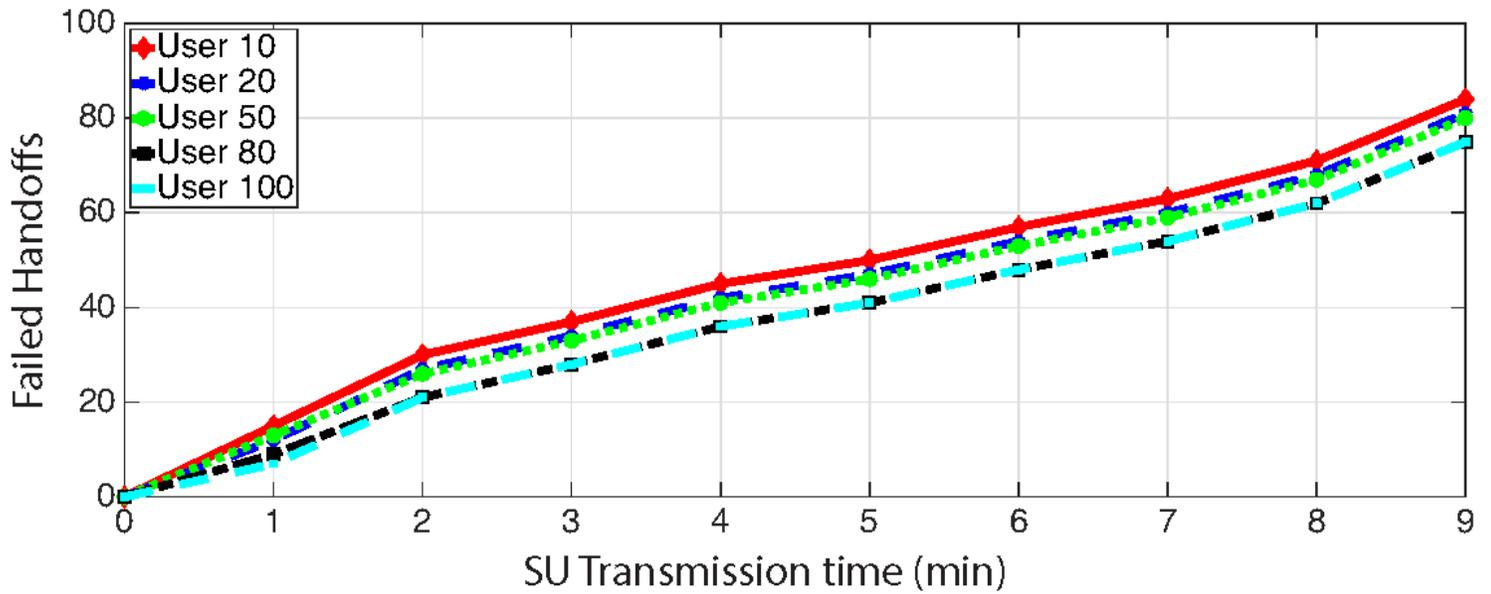
b. BE LT

Figure 12

Failed handoffs for FFAHP BE



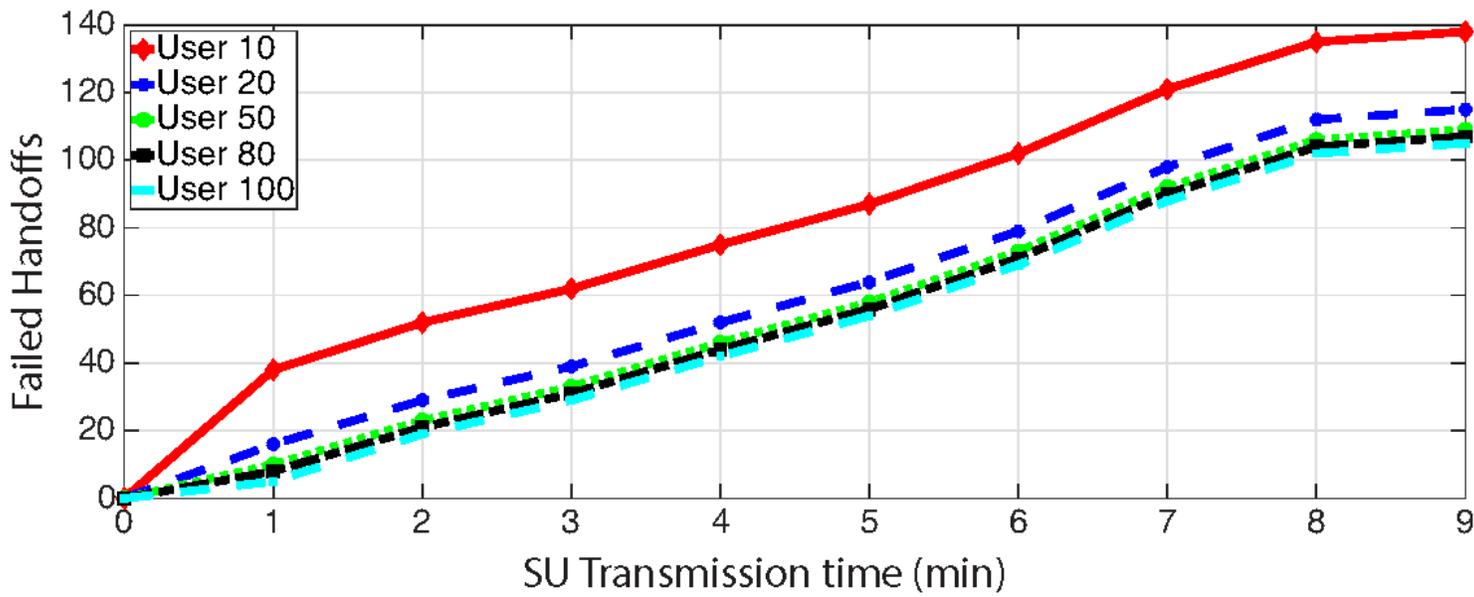
a. RT HT



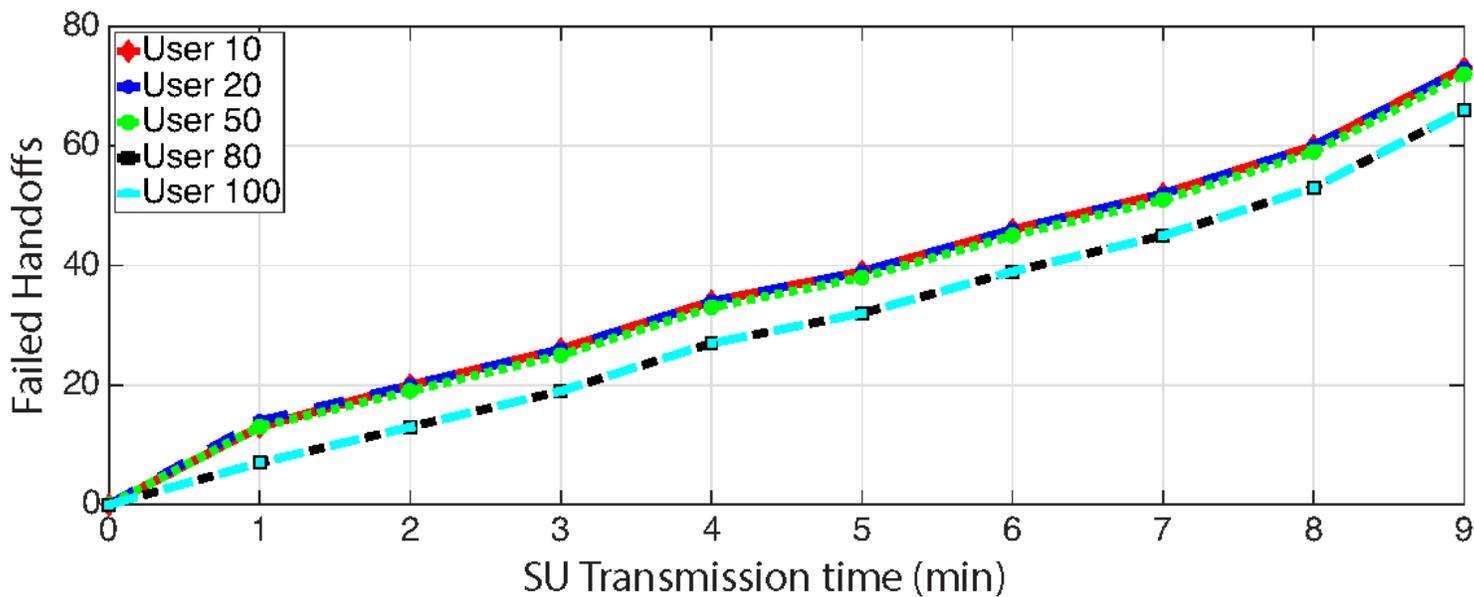
b. RT LT

Figure 13

Failed handoffs for SAW RT



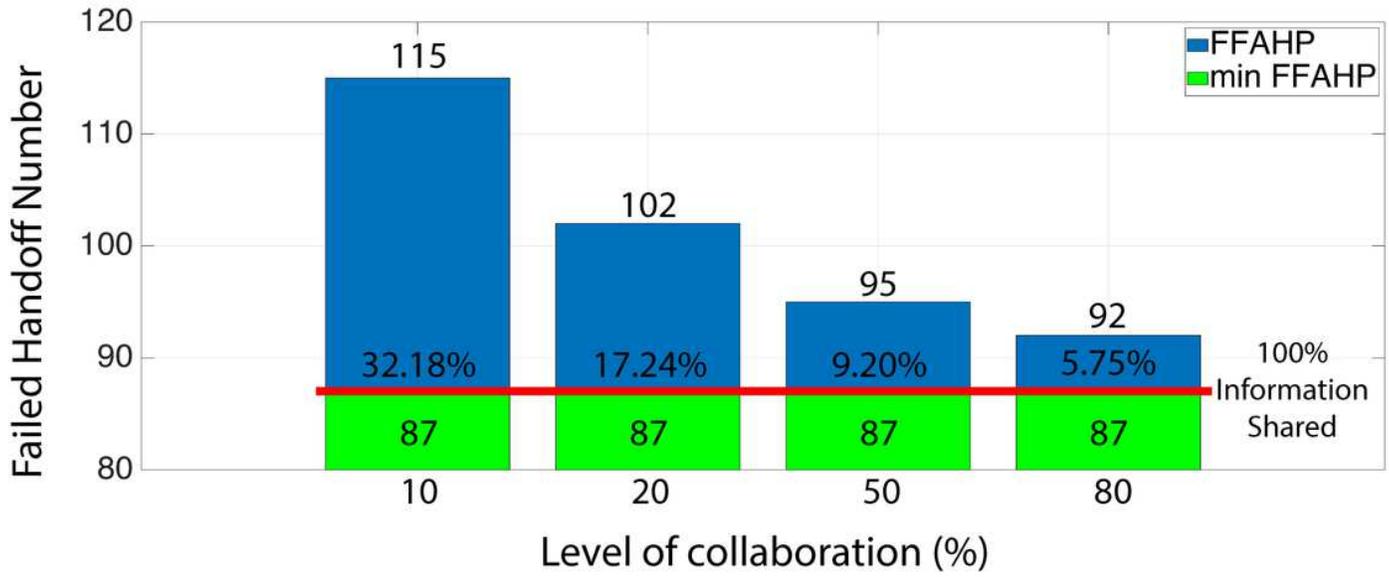
a. BE HT



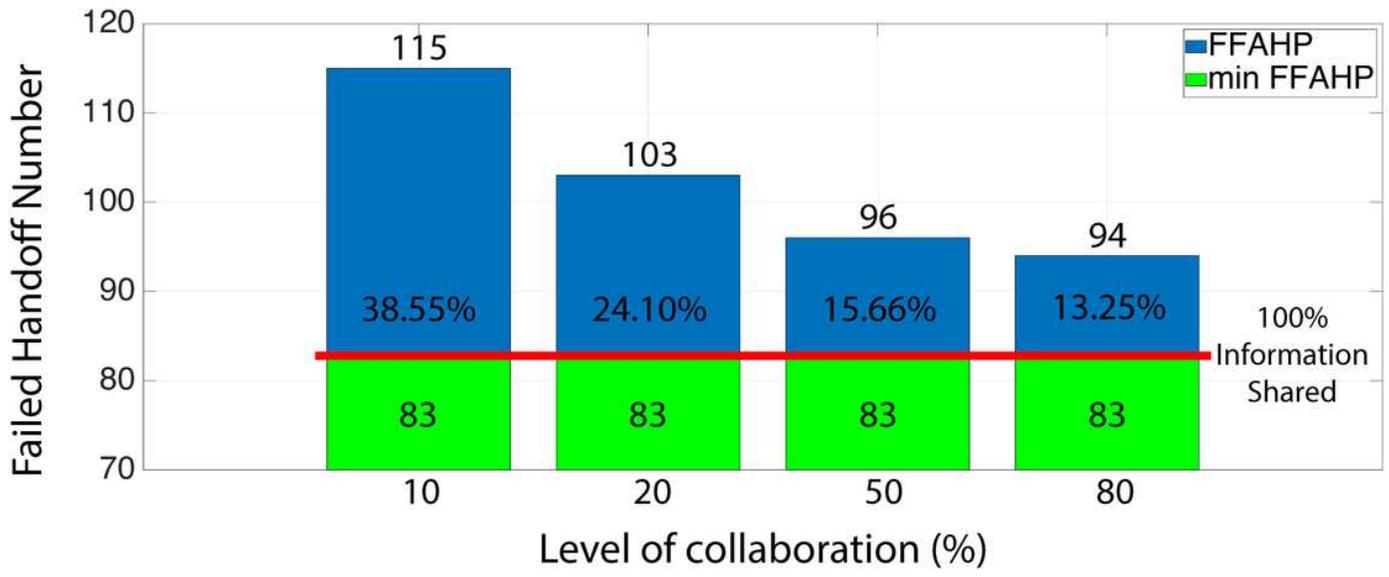
b. BE LT

Figure 14

Failed handoffs for SAW BE



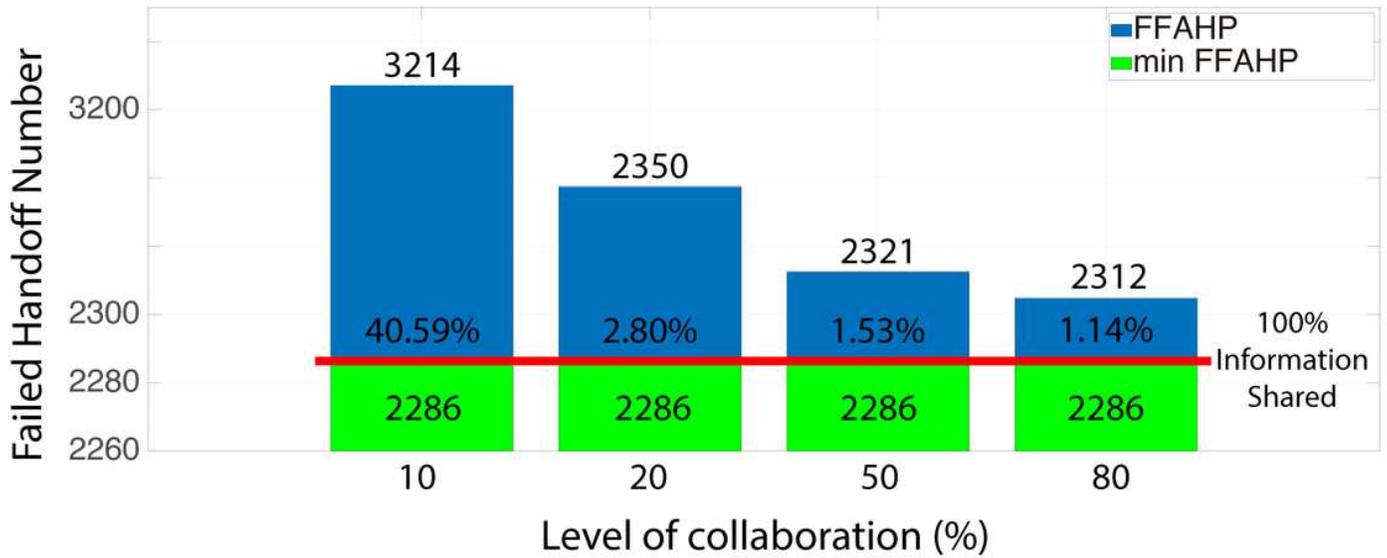
a. RT HT



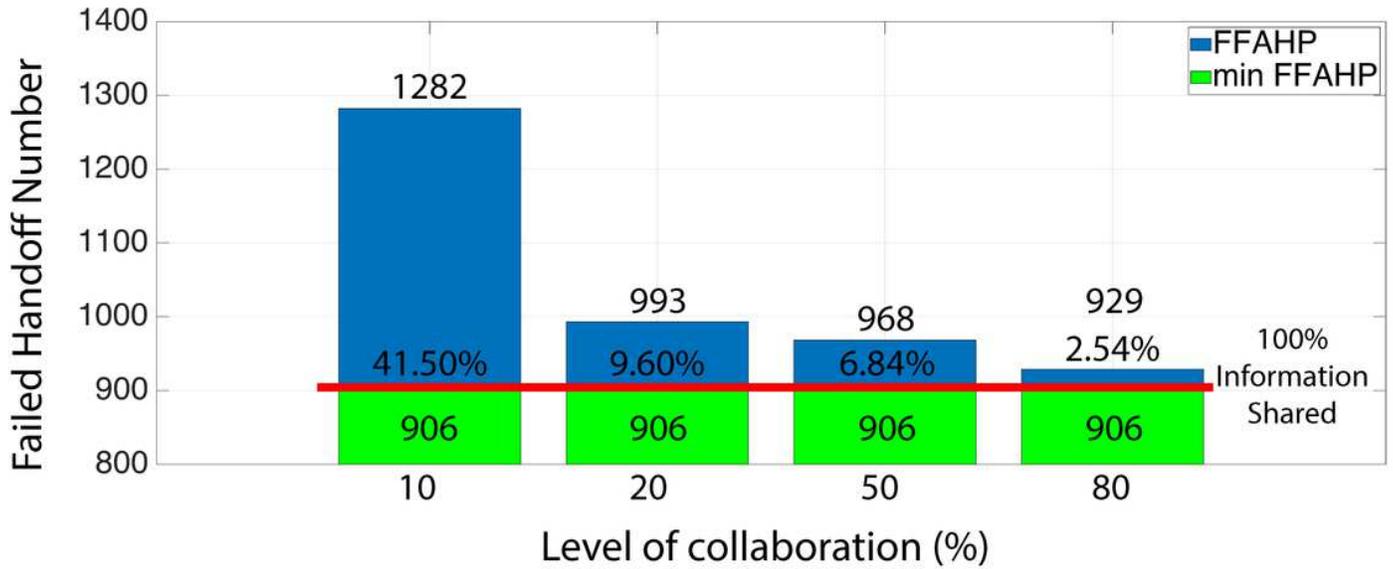
b. RT LT

Figure 15

Failed handoffs for FFAHP with real time (RT) service



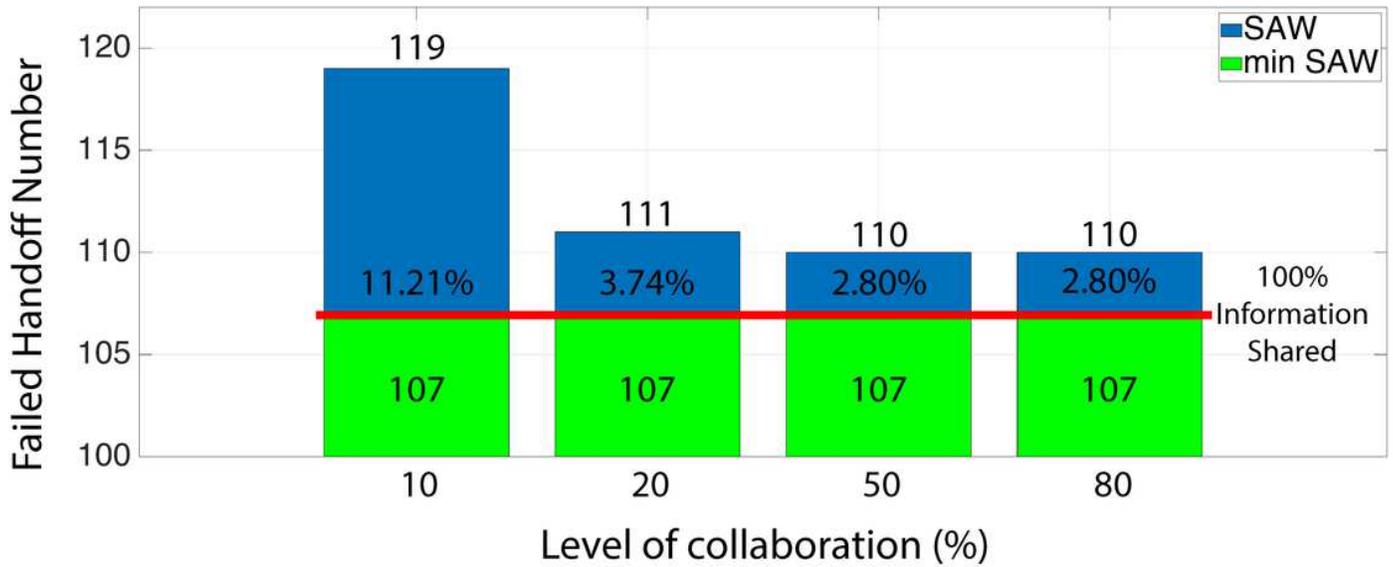
a. BE HT



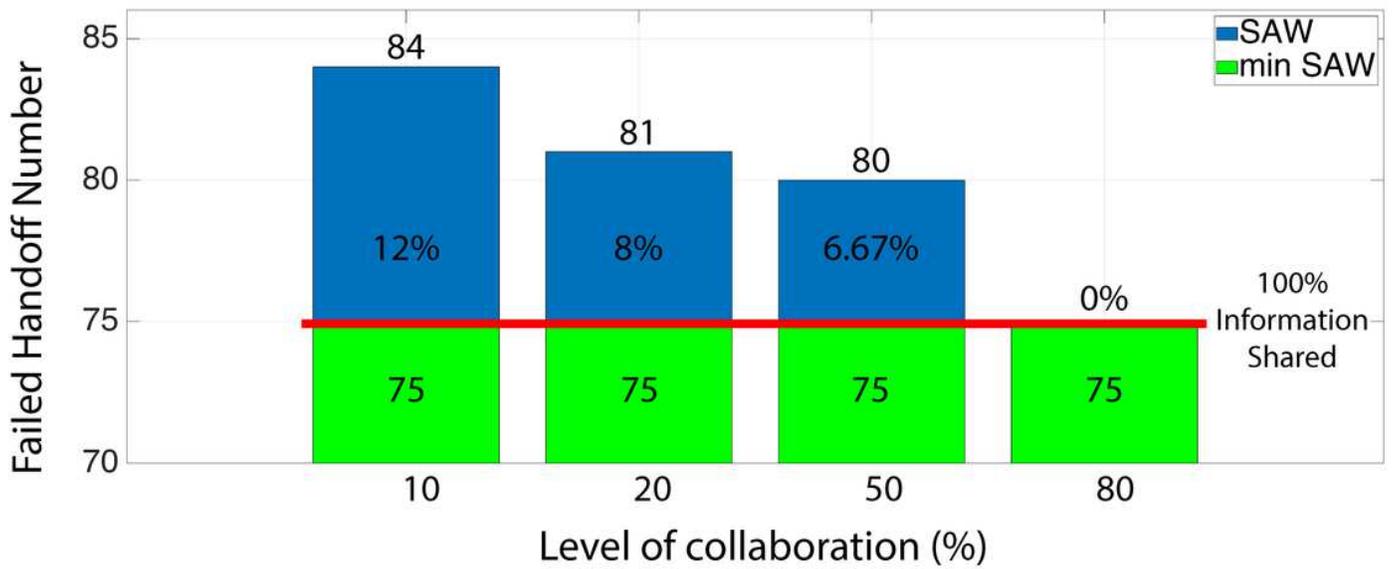
b. BE LT

Figure 16

Failed handoffs for FFAHP with better effort (BE) service



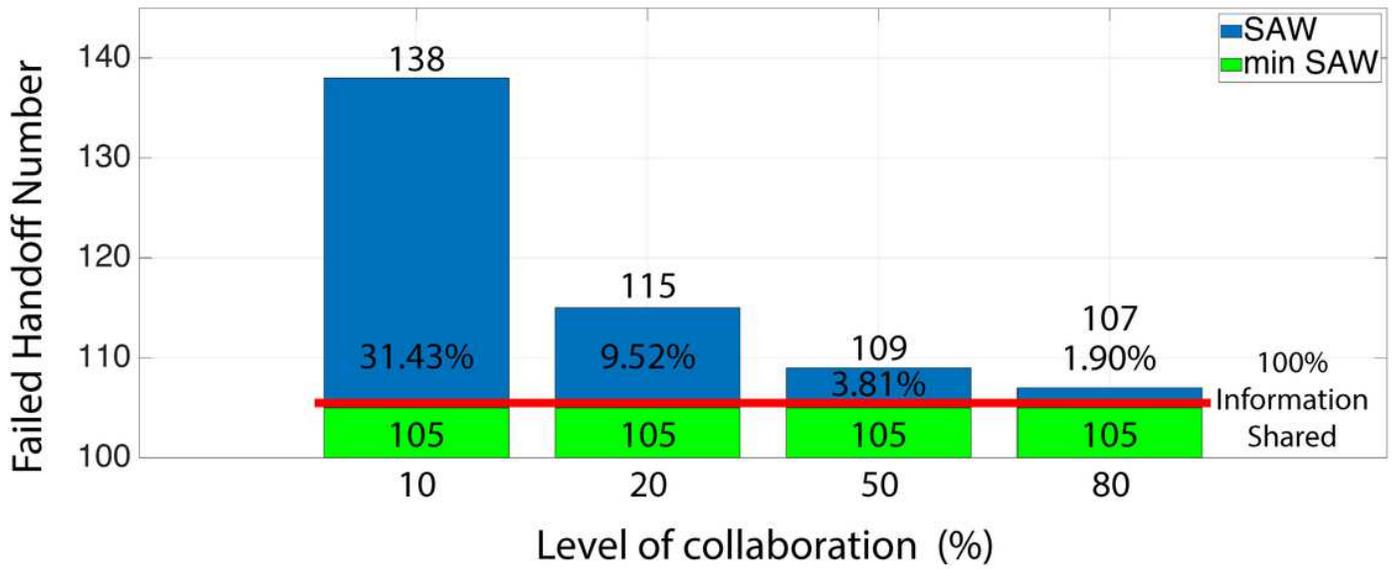
a. RT HT



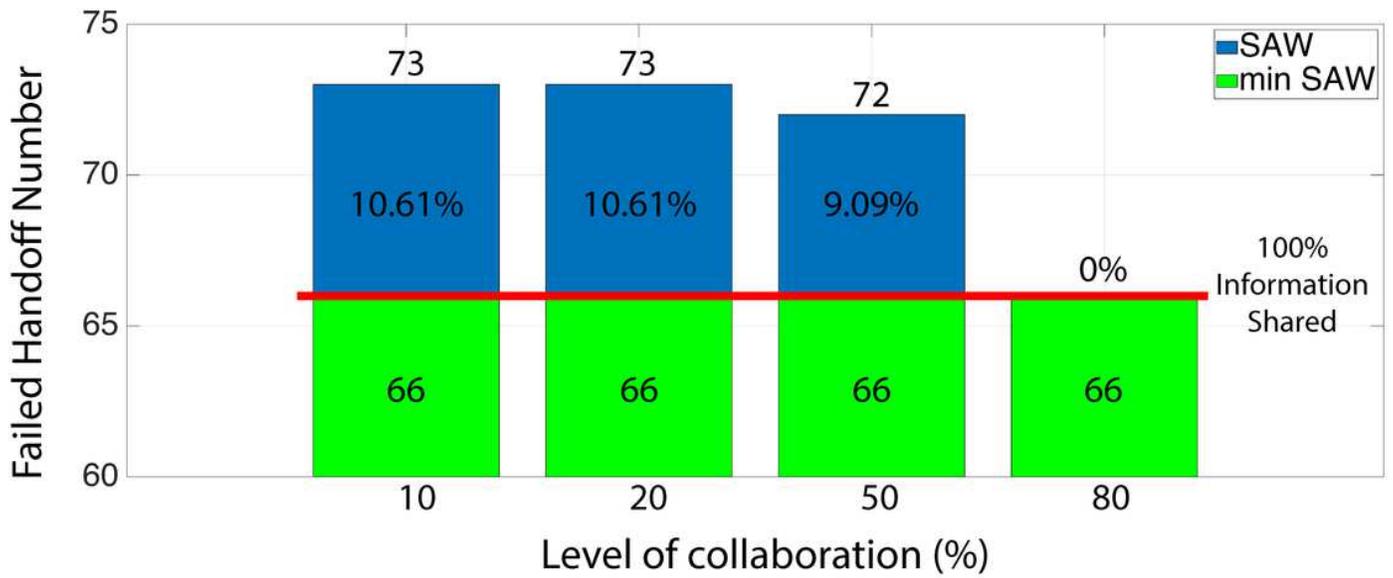
b. RT LT

Figure 17

Failed handoffs for SAW with real time (RT) service



a. BE HT



b. BE LT

Figure 18

Failed handoffs for SAW with better effort (BE) service