Standard Compliant Channel Selection Scheme for TV White Space Networks

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***Abstract*—In television white space networks, secondary users are required to query an authorised geo-location spectrum database (GSDB) in order to determine the vacant channels or white spaces. While recent development of the Protocol to Access White Spaces (PAWS) by the Internet Engineering Task Force (IETF) is intended to standardize communication between the GSDB and white space devices for sharing spectrum white spaces (WSDs) and their related parameters, the mechanism for channel selection remains an open issue. In this paper, an Analytic Hierarchy Process (AHP) based scheme is proposed for optimal channel decision. The best channel is selected from a pool of available channels provided by the GSDB. Each channel is ranked based on the current class of service offered (either best effort or real time) offered as well as multiple attributes sourced from GSDB. The numerical results show that the proposed scheme is capable of selecting the best channels to satisfy the users' preferences with lower decision latency than the compared existing solution.**

Keywords—Analytic hierarchy process, Channel selection, Geo-location spectrum database, TV white space, White space device.

I. INTRODUCTION

The television white spaces (TVWSs) are portions of radio frequency (RF) spectrum on the TV band that are not being used at a given time and location by the licensed TV incumbents as a result of frequency planning (guard bands) and as a by-product of the global digital switch over process. In our prior work on TV spectrum measurements in both urban and rural areas in Southern Africa, we found that TVWS availability ranges between 100 to 300 MHz [1], [2]. Due to their favourable propagation characteristics, the TVWSs are being considered for providing broadband access in rural areas [3]–[5]. Successful sharing of TV spectrum between broadcast and broadband services depends on adoption of dynamic spectrum access (DSA) regulatory approach. In DSA based broadband networks, cognitive radios (CRs) or white space devices (WSDs) operate as secondary users (SUs) who access the white spaces without creating interference to the licensed or primary users (PUs). Two techniques are commonly considered for discovering the white spaces: *spectrum sensing* and *geo-location spectrum database (GSDB)* [6]. Experimental TVWS broadband networks using GSDBs have been piloted in many parts of the world including South Africa [7].

Recently, the Internet Engineering Task Force (IETF) released an Internet draft on the Protocol to Access White Spaces (PAWS) which is a standardized protocol used for sharing TVWS and their related parameters between the WSDs and GSDBs [8]. While PAWS addresses the communication between the GSDB and WSDs, the mechanism for selecting or allocating the channels to the WSDs remains an open issue. In a large TVWS network that consists of multiple WSDs, optimal channel decision and allocation to satisfy all SUs' quality of service (QoS) requirements, while managing total interference, was found to be an NP-complete problem [9]. As a result, heuristic methods are being considered for finding optimal solutions.

One of the most critical challenges on channel decision in TVWS networks is the heterogeneous propagation characteristics among various TV spectrum bands [10]. This is due to the wider range between the lower TV channel (channel 21, at 470 MHz) and the upper channel (channel 48 at 694 MHz) which exhibits different interference relationships among the WSDs. There are several applications operating on the TV band such as Programme Making and Special Event (PMSE) services which are characterised by narrow-bands (in the range of 200 kHz) as compared to the 6 or 8 MHz wideband TV channel. PMSE devices may include hand-held devices which may use a combination of broadcasting (e.g. TV reception) and broadband such as an Internet Protocol Multimedia Subsystem (IMS) clients [11]. As a result, the TVWSs will not have equal channel bandwidth. Hence it is important to consider the user preferences, white space channel characteristics and other network attributes when designing channel selection solutions.

Over the past decade, multiple attribute decision making (MADM) techniques have been considered to address the decision making process in integrated and heterogeneous wireless networks [12]–[15]. As a subset of MADM technique, Analytic Hierarchy Process (AHP) provides a powerful and robust step-by-step decision-making process through pairwise comparisons that can be used to combine qualitative and quantitative factors for prioritizing, ranking and evaluating alternatives [16]. By using the hierarchical approach, a complex problem is broken-down into smaller and less-complex problems for simplified decision making. This makes AHP the most preferred MADM technique where several attributes, such as throughput, bandwidth, delay, QoS requirements, etc., are considered in decision-making process. In [12], AHP was applied to solve a network selection problem in an integrated wireless local area network (WLAN) and 3rd generation cellular networks. Rodriguez-Colina *et al.* used AHP for spectrum decision making in cognitive radio networks (CRNs) [13]. Ramli *et al.* applied AHP to make a decision on how to fairly allocate the spectrum licenses [14]. For TVWS specific networks, a channel allocation algorithm based on Simulated Annealing (SA) is proposed in [9]. A distributed spectrum allocation algorithm based on spectrum fragmentation and non-uniform interference relationship among multiple access point (APs) is proposed in [10]. Both [9] and [10] offload the channel decision functionality to the local-white space database. While this might be a suitable solution for a small geographical area where such a GSDB is located within the vicinity of the TVWS network, it might not be feasible for wider TVWS network deployments where a national GSDB is located far away from the TVWS network. For instance, TVWS network might be deployed in a rural or remote area while a GSDB can be located hundreds of kilometres away or located in the cloud (or in a different province or country). In such scenarios, it becomes important for a TVWS base station (TVWS-BS) to manage and coordinate spectrum decision and allocation to its associated customer premises equipments (CPEs) or WSDs. Furthermore, the existing schemes, such as the Simulated Annealing (SA) scheme [9] are computationally complex and time-consuming, especially when determining and choosing channel parameters [9].

In this paper, we propose an AHP-based channel decision scheme which considers the user preferences and channel conditions based on the information collected from the national GSDB. Our proposed scheme uses AHP to determine the weights and ranking of suitable channels taking into account the white space channel attributes such as the available bandwidth, available channel occupancy time and the allowed transmit power limit. Based on the weights and ranking of white space channels (or alternatives), the national regulatory rules on PU protection against harmful interference are considered before the best channel (i.e. channel with higher relative weight) is selected and allocated to the WSDs. By considering these attributes, our scheme is compliant to the PAWS protocol and can be implemented to most WSDs because it is portable and not computationally complex.

The remainder of this paper is organized as follows. Section II describes the system model considered in this paper. An overview of AHP and the relevant PAWS messages with their parameters are discussed in Section III. The proposed AHP-based channel decision model is presented in Section IV. Section V presents and discusses the numerical results. The paper is concluded in Section VI.

II. SYSTEM MODEL

A. Network Scenario

We consider a centralised TVWS network consisting of a single TVWS base station (TVWS-BS) with three sectors and multiple fixed WSDs or CPEs which provide broadband access to several schools. This is the same network scenario used during our recent TVWS trials in Cape Town, South Africa [7]. The TVWS-BS co-exists with a single frequency network TV broadcast system where multiple transmitters are co-located on a single mast.

B. Access to GSDB

The TVWS-BS is connected to one of the approved GSDBs through either fixed line or alternative wireless technology (such as satellite links) which also provides the back-haul. Based on the Cape Town TVWS trial network, each of the three sectors operates on a different TV channel (thus, a minimum of three channels are required to provide minimum connectivity to the schools). Once switched "On" the TVWS-BS establishes an HTTP session with the national GSDB in order to register and initiate a query for available channels. The messages between the TVWS-BS and the GSDB are standardized by the PAWS [8], while messages between the WSD and the GSDB is use dependent, i.e. not standardized by the PAWS. Once selected a channel for itself, the TVWS-BS then uses each WSD's geo-locations (which are readily known to the TVWS-BS) to query the GSDB for more available channels using the AVAIL_SPRECTRUM_BATCH_REQ request. The WSDs are also called slaves because they do not have direct access to the GSDB [8]. Depending on the amount of traffic demand or class of service (i.e. real-time or best effort) by the WSDs and the distance from the BS, the best suitable number of channels will be selected (also depending on the availability of white spaces). Finally, by sending a SPECTRUM_USE_NOTIFY, the TVWS-BS notifies the GSDB of the selected channels used by the entire network. This will assist the GSDB not to provide the same list of available channel to other secondary networks, thereby preventing any co-channel interference [17].

C. PU Protection Against Interference

By relying on the GSDB for white space availability, interference to the PUs is already minimized since the GSDB will only provide a list of channels which are not occupied by the PUs. However, there are some restrictions on the allowed maximum transmission power depending on whether the TVWS channel being used is adjacent to the PU channel or more than $n \pm 1$ away from the PUs channel (where n is the primary channel number). The regulators can determine the allowed transmission power for adjacent and non-adjacent channels as specified by the FCC [3]. Operation on adjacent channels is likely to be kept lower than the operation on other channels which are more than $n \pm 1$ away from the primary channels. Therefore, it is important for the TVWS-BS to carefully select the best channel for its associated WSDs taking into account the transmit power limit set by the national regulator. The proposed system should have a list of all primary channels which must be avoided when deciding the best channels to select. This list is also useful to the TVWS-BS when checking for the adjacent primary channels.

We assume the primary TV channel size of 8 MHz wide. Thus the list of occupied frequency blocks are ordered and stored as $F_{L,i}$ and $F_{U,i}$, which represent the i^{th} lower and upper channel edge frequencies. The PU Protection Rules is determined by checking whether the startHz and stopHz values of each white space channel is adjacent to the lower and upper edge frequencies of the primary channels, respectively. Thus, if startHz = $F_{U,i}$ (where i is the index of the busy or occupied primary channels) then the lower edge of the available channel is adjacent to the upper edge of the primary channel. And if stopHz = $F_{L,i}$, then the upper edge of the available channel is adjacent to the lower edge of the primary channel. To represent whether the white space channel is adjacent to the $n \pm 1$ primary channels, we define $\mathbf{PU_{n\pm1}}$ as in equation (1):

$$\mathbf{PU_{n\pm1}} = \begin{cases} 1, & \text{available channel is adjacent to the PUs,} \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

III. AHP OVERVIEW AND PAWS PARAMETERS

Before explaining how the model works, we start by providing a brief overview or introduction of the AHP and the PAWS message and parameters relevant to this paper.

A. Analytic Hierarchy Process (AHP) Overview

First introduced by Saaty in the late 1970's, AHP is a theory of measurement through pairwise comparisons that can be used to combine qualitative and quantitative factors for prioritizing, ranking and evaluating alternatives [16]. Over the past thirty decades, AHP has been applied in different fields such as finance, politics, personnel, sports, social sciences, engineering and medical field [18]. AHP is generally performed in five steps (S1 - S5) [16]:

S1: Structure a problem as a decision hierarchy of independent decision elements where the goal is at the top level and the set of alternatives on the lowest level;

S2: Collect relevant data about the decision elements;

S3: Compare the decision elements pairwise on each level based on their importance to the elements in the level above, thereby constructing a comparison matrix;

S4: Calculate the relative priorities of decision elements in each level; and

S5: Synthesize the above results to achieve the overall weight of each decision alternative.

B. Weight Determination using AHP

From the developed pairwise comparison matrix A, the global priority vector (PV) or weights w are found using the eigenvector method. So, w is found by solving:

$$Aw = \lambda_{max} w, \tag{2}$$

where λ_{max} is the largest or principal eigenvalue of matrix A. Global weights are determined by making pairwise comparisons of the alternatives with respect to the available criteria.

After completing step 5, the consistency test, which is one of the most important AHP features, is performed to measure the degree of inconsistency during the pairwise comparison. The consistency test is performed by first computing the matrix's consistency index (CI) as in (3):

$$CI = \frac{\lambda_{max} - n}{n-1}, \tag{3}$$

where n is the total number of activities in the pairwise matrix. Using the CI, we then calculate the consistency ratio (CR) as:

$$CR = \frac{CI}{RI}, \tag{4}$$

where RI is the random index related to the order (n) of judgement matrix as calculated in [16]. The CR of less than 10% ($CR \leq 0.1$) is acceptable (i.e. the pairwise comparison process was consistent). If the CR is higher than 10%, the process was inconsistent and the pairwise comparison must be re-evaluated. Finally, the results of the AHP are conveniently captured and visualized in the form of a decision profile, which offers a convincing view of the results of rating the alternatives.

C. Available Spectrum Response Message

According to PAWS protocol, attributes are extracted from the AVAIL_SPECTRUM_RESP message which is sent to TVWS-BS by the GSDB [8]. This message contains several parameters which includes ***timestamp, spectrumSchedules, maxTotalBwHz, maxContiguousBwHz**, etc.*. The most important parameters used in our model are *maxTotalBwHz and spectrumSchedules* which are explained next.

1) ***The maxTotalBwHz Parameter:*** The maxTotalBwHz provides the maximum total bandwidth (in Hz) which may or may not be contiguous [8].

2) ***The spectrumSchedules Parameter:*** Provides a combination of EventTime and Spectrum elements. The EventTime element specifies the start (*startTime*) and stop (*stopTime*) times of an event. The TVWS-BS will then use these elements to calculate how long each white space channel is likely to be available.

The *spectrum* element in the spectrumSchedules parameter consists of two parameters which characterizes a list of frequency ranges and permissible power levels for each range. The *frequencyRanges* lists the maximum permissible power levels within a frequency range.

IV. PROPOSED CHANNEL DECISION SCHEME

The proposed channel selection model is performed based on the flowchart shown in Fig. 1. We assume that the TVWS-BS is authorised and registered with the national GSDB. The model starts when the TVWS-BS queries the GSDB after performing the necessary initialization and authentication processes [8]. Once the TVWS-BS receives the list of spectrum from the GSDB, it extracts important parameters or attributes which will be used for decision making. The maxTotalBwHz parameter is important for our model to decide whether to perform AHP analysis for spectrum selection or not. At least one full channel (equivalent to 8 MHz bandwidth) should be available for the the AHP analysis to be conducted. If no channel is available, the TVWS-BS will query the GSDB after a predefined period of time until at least more than one channel is available to allow the channel allocation process to start.

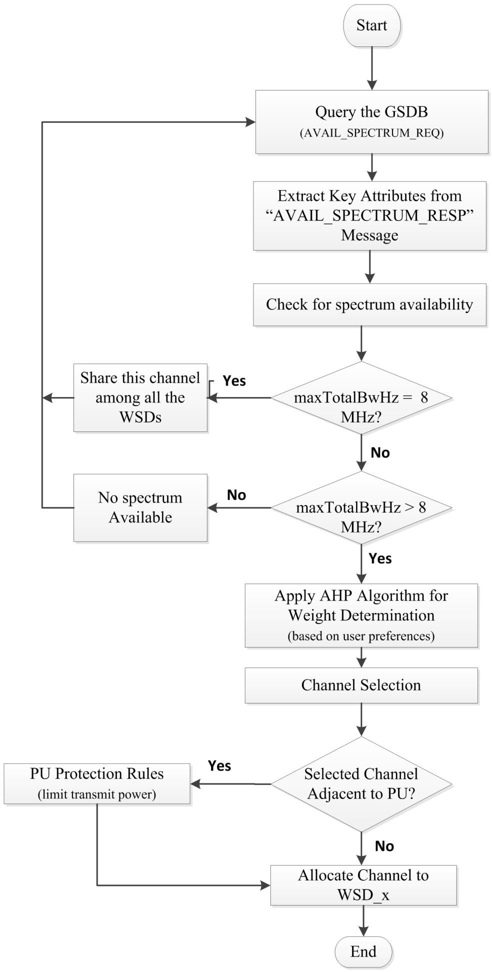


Fig. 1: Proposed channel selection scheme flowchart

A. White Space Channel Attributes Collection

Based on the above parameters, the following three channel attributes are defined as criteria during the AHP analysis:

Bandwidth = *stopHz - startHz*,

where startHz and stopHz are the start and stop of the frequency range in Hz, respectively and these values are sourced from the frequencyRanges element. This represents the usable channel width which may vary from a few kHz to a few MHz depending on whether there are contiguous channels or not. The reasons for such variable channel width are motivated by the types of other SUs (such as IEEE 802.22 or IEEE 802.11af standards) and PU technologies (such as narrowband PMSE).

Transmit Power = *maxPowerDBm*.

Event Time = *stopTime - startTime*,

where startTime and stopTime are the inclusive start and end of the channel availability.

B. Proposed Spectrum Decision Hierarchy Structure

Fig. 2 shows the proposed AHP hierarchy structure where the top level presents the main goal on the structure, which is to select the best available channel. The selection of the channels is based on the user's preferences which requires a specific QoS for each class of service. In this paper, we consider two classes of service (CoS): *Real Time (RT)* and *Best Effort (BE)*, which are on the second level of the hierarchy. On the third level of the hierarchy are the three independent criteria to be compared when selecting the channels. At the bottom of the hierarchy are at least four alternative channels which are compared in order to select the best channel.

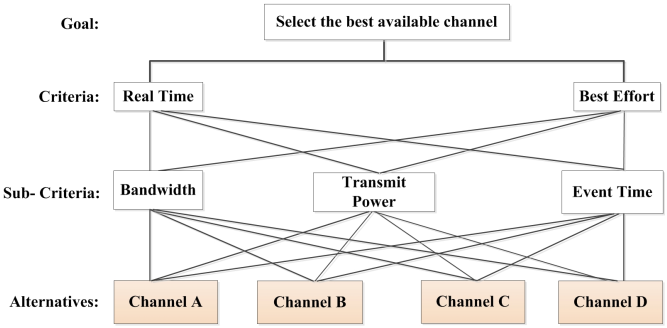


Fig. 2: Channel Selection hierarchy structure

C. Deciding the Best Channel

The final stage of the AHP analysis is reached when the overall weight vector $\mathbf{W}$ for each alternative (available channels) is found. From this weight vector, the best channel C_{best} is selected by observing the highest weight from the alternatives as shown in equation (5).

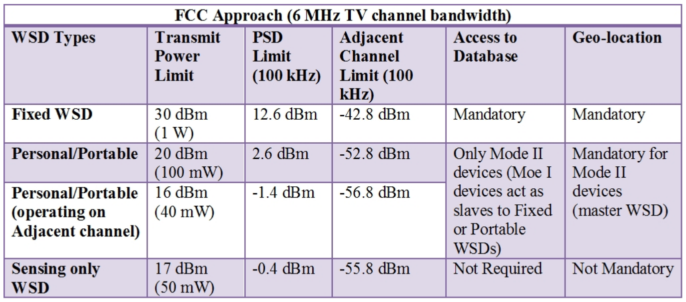
$$C_{best} = \max(\mathbf{W}) \tag{5}$$

where $\mathbf{W} = \{w_1, w_2, \ldots, w_n\}$ and represents the overall weights for each alternative. However, if the consistency ratio (CR) was found to be bigger than 10%, the above analysis is repeated until the CR is less than 10%. In the next section we present the numerical results to demonstrate our channel decision scheme.

D. PU Protection Rules

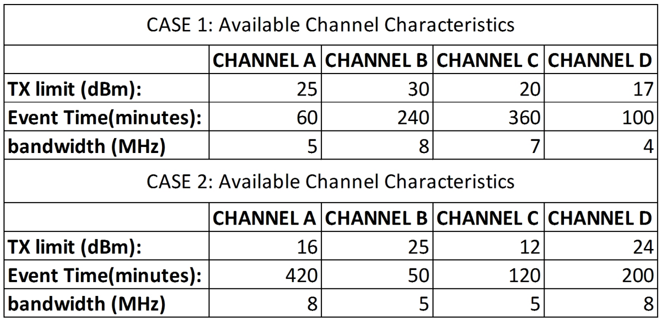
Once the best channel is selected, we use equation (1) to check whether the selected channel is adjacent to the primary channel or not. If it is adjacent, we apply the PU Protection Rules by making sure that transmit power is kept within the limit for adjacent channel operations. Table I shows the allowed transmission power for adjacent and non-adjacent channels as specified by the FCC [3]. The FCC limits are used here as a guideline and they may vary according to the individual country's regulatory power limits. If the selected channel is not adjacent to any PU, the channel is allocated to the WSD at the default transmit power. The default transmit power is the power that was provided by the GSDB. Once all the channels are selected and allocated to the WSDs, the TVWS-BS uses the SPECTRUM_USE_NOTIFY message to update the GSDB about the selected channels. Then the GSDB will mark those channels as unavailable.

TABLE I: FCC Compliant WSD Operation Characteristics



FCC Approach (6 MHz TV channel bandwidth)					
WSD Types	**Transmit Power Limit**	**PSD Limit (100 kHz)**	**Adjacent Channel Limit (100 kHz)**	**Access to Database**	**Geo-location**
Fixed WSD	30 dBm (1 W)	12.6 dBm	-42.8 dBm	Mandatory	Mandatory
Personal/Portable	20 dBm (100 mW)	2.6 dBm	-52.8 dBm	Only Mode II devices (Moe I devices act as slaves to Fixed or Portable WSDs)	Mandatory for Mode II devices (master WSD)
Personal/Portable (operating on Adjacent channel)	16 dBm (40 mW)	-1.4 dBm	-56.8 dBm		
Sensing only WSD	17 dBm (50 mW)	-0.4 dBm	-55.8 dBm	Not Required	Not Mandatory

TABLE II: Two case scenarios with available channels characteristics for Real-Time and Best-Effort CoS



CASE 1: Available Channel Characteristics				
	CHANNEL A	**CHANNEL B**	**CHANNEL C**	**CHANNEL D**
TX limit (dBm):	25	30	20	17
Event Time(minutes):	60	240	360	100
bandwidth (MHz)	5	8	7	4
CASE 2: Available Channel Characteristics				
	CHANNEL A	**CHANNEL B**	**CHANNEL C**	**CHANNEL D**
TX limit (dBm):	16	25	12	24
Event Time(minutes):	420	50	120	200
bandwidth (MHz)	8	5	5	8

V. RESULTS AND DISCUSSIONS

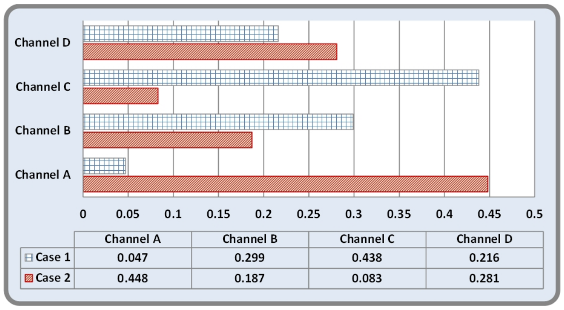
In this section we present simulation results related to the channel selection based on the white space attributes provided by the GSDB as well as the user preferences for the CoS (i.e. RT and BE).

A. Simulation Scenario

In order to demonstrate our scheme, we consider a scenario where the TVWS-BS queries GSDB for available white spaces on behalf of its associated WSDs. Four channels with different characteristics are returned by the GSDB and the TVWS-BS must at least select one channel to allocate to each WSD. We evaluate two cases: one for RT CoS and the other one for BE services. Table II shows characteristics of the available channels received by the TVWS-BS from the GSDB for both RT and BE CoS.

B. Discussions

After receiving a set of available channels from the GSDB, the scheme extracts and computes the values of key parameters such as channel bandwidth, event time and the allowed transmission power. Using the AHP algorithm, the weights of these three parameters or criteria are determined for both RT and BE CoS, depending CoS for the active application to be transmitted. The weights and consistency ratio (CR) for the three criteria are shown in Table II. These weights shows the important relationship between the criteria and CoS. The criteria with the highest weight correspond to the highest degree of importance for the CoS considered. For instance, in RT services, the event time (duration of channel availability) and transmit power are more important than the channel bandwidth. For BE applications, of course the bandwidth is more important, followed by the transmit power. Furthermore, we have shown the CR for each CoS, which was found to be less than 10%. This means that our judgements in the pairwise comparison matrix were consistent.



	Channel A	Channel B	Channel C	Channel D
▦ Case 1	0.047	0.299	0.438	0.216
▨ Case 2	0.448	0.187	0.083	0.281

Fig. 3: Decision profile for channel selection in RT CoS.

TABLE III: Weights of criteria for RT and BE services

Criteria	**Real-Time**	**Best Effort**
Bandwidth	0.072	0.637
Transmit Power	0.279	0.258
Event Time	0.649	0.105
Consistency Ratio (CR)	0.056 (5.6%)	0.033 (3.3%)

Using the weights of the criteria, we then a developed pairwise comparison matrix comparing the four available alternative channels against each criterion (i.e. bandwidth, event time and transmit power). The same procedure that we used to find the criteria weights was followed for each case scenario as shown in Table II. Fig. 3 shows the decision profiles or relative weights for each of the four alternative channels RT CoS. It can be seen that our scheme was able to select *Channel C* for case 1 because it has the longest available time (event time) than other channels.Despite having the lower bandwidth and transmit power than*Channel B*, as well as lower transmit power than *Channel A*, *Channel C* is suitable for RT services where the SUs would not want to experience some call drops due to shorter event time. For case 2, *Channel A* was selected for RT transmission. Again, this decision was mainly based on the high degree of weight given to the event time criteria for RT services.

In Fig. 4, the BE CoS decision profiles for each of the four available channels are shown. For case 1, *Channel B* has the highest weight and was selected for BE transmission. This is mainly due to the size of the channel bandwidth which is higher than other alternative channels. As shown in Table III, BE CoS allocated more weight to the bandwidth criterion followed by the transmit power. Event time is ranked lower for BE services because such services are delay tolerant than RT services. Thus, the higher the channel bandwidth, the higher the transmission throughput. If the selected channel's event time elapses, the TVWS-BS will have enough time to allocated a new channel without compromising the SU's QoS.

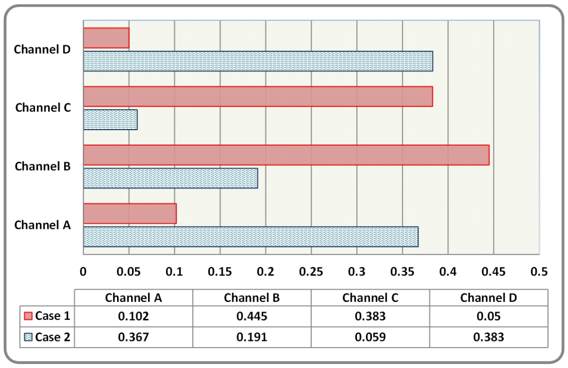


Fig. 4: Decision profile for channel selection in BE CoS.

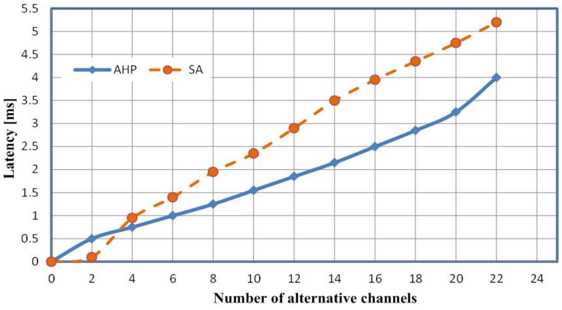


Fig. 5: Performance of AHP and SA schemes with respect to simulation latency

Fig. 5 compares our AHP-based scheme to the SA approach (used in [9]) based on the decision making average simulation latency as a function of alternative channels. We compared the simulation latency of each scheme for selecting the best channel between 2 to 22 alternative channels. The delay in SA scheme is due to the complexity of choosing the parameters before selecting the best channel for the available alternatives. Instead of a hierarchical structure for criteria and sub-criteria, which is used in AHP, SA scheme is based on simulating a random walk on the set of states [9]. Furthermore, the AHP scheme is more convenient to evaluate only two alternatives at a time, which makes it robust especially when dealing with a large number of alternatives. Whereas SA requires multiple combinatorial optimization steps to converge. Since the latency and low computational complexity are crucial parameters for a spectrum decision scheme, especially in DSA based networks [19], our proposed scheme performs best.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have developed an AHP-based channel selection scheme which jointly considers multiple parameters provided by the GSDB as well as the users' preferences. It was shown that the proposed scheme performs adequately and yields acceptable and accurate results in selecting the best channels for different WSDs in a TVWS network. The scheme was also found to perform with low latency and easy to implement when compared to other existing schemes. Future work includes the integration of the AHP scheme with optimization techniques in order to allow optimal selection of the channels, and the use of a game theoretic approach to analyse the model for fairness and energy efficiency.

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