Proactive dynamic spectrum access based on energy detection

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Abstract—**Cognitive radio (CR) is a promising next generation technology, which aims to utilise radio frequency spectrum resources in an efficient manner. CR applications should be able to sense a primary user (PU) by using, among other techniques, energy detection. In this paper, the methodology behind energy detection is discussed and a theoretical expression for the probabilities of missed detection and false alarm, for an unknown deterministic signal, is provided. This theoretical expression has been shown to predict receiver operator characteristic (ROC) detection results, which would typically be encountered during energy detection of a television (TV) band. The ROC results further suggest that a signal-to-noise ratio (SNR) value of higher than 11 dB would be required under Rayleigh fading channel conditions in order to conform to the detection characteristics imposed by the IEEE 802.22 standard. Once spectrum sensing has been performed, a secondary user (SU) may be allocated radio resources. A proactive approach to dynamic spectrum access is employed in this paper, where channel switching decisions are based on near future channel occupancy predictions. Results indicate that increasing the number of channels available to the SU, as well as the number of predicted near future time slots to an optimal point, significantly improves the channel allocation process. For the channel conditions simulated in this paper, results indicate that the optimal number of channels that should be available to the SU is eight and that the optimal number of near future time slots that should be utilised to perform proactive dynamic spectrum access is five.**

Index Terms—**channel switching, cognitive radio, energy detection, IEEE 802.22, proactive dynamic spectrum access.**

I. INTRODUCTION

The concept of cognitive radio (CR) was proposed by Mitola [1], [2] and builds upon software-defined radio techniques, although the cognitive concept was already previously known [3]. The defense advanced research project agency (DARPA), subsequently investigated dynamically managing spectrum for neXt Generation communication systems applications (for instance CR) [4]. The CR concept currently involves thinking of frequency spectrum in terms of white spaces. A white space is a band of frequencies assigned to a primary user (PU), that at a particular time and geographic location are not actually being utilised by this PU [3]. In a CR network, a secondary user (SU) would then be allowed to opportunistically use this white space, provided that it does not interfere with PU transmission. This process would consequently allow for more efficient use of the frequency spectrum.

While the CR concept is still in its conceptual stage, the benefits of spectrum sharing have already been demonstrated by the coexistence of the IEEE 802.11 (Wi-Fi) and IEEE 802.15 (Bluetooth) networks [5]. Owing to the cost of network infrastructure and setup, the provision of broadband access to rural areas is a challenging issue. Cognitive radio technology aims to tackle this problem through the proposal of the first IEEE 802.22 wireless regional area network (WRAN) standard. Technical proof of this concept would clear the way for regulatory approval.

Since steps need to be taken to avoid collisions with the PU, the use of channel occupancy predictions to perform proactive channel selection has been suggested to aid in the opportunistic spectrum allocation process [6]–[8]. In this paper a proactive approach to dynamic spectrum access is discussed. This approach attempts to perform proactive channel switching from near future predictions of PU activity that are based on historical PU statistics. The historical information is obtained through an energy detection based spectrum sensing process. Accurate spectrum sensing is thus critical to the channel allocation process.

The paper is structured as follows: Section II presents a characteristic overview of the IEEE 802.22 WRAN standard (implementation of CR over television (TV) white spaces). Section III provides a discussion of the energy detection method, which will be used to detect a DVB-T2 [9] transmission (this type of energy detection would typically be employed by a SU operating under the IEEE 802.22 standard). Section IV describes the proactive approach to dynamic spectrum access. This is followed by Section V, where conclusions about the study are drawn.

II. OVERVIEW OF IEEE 802.22

One of the key objectives of the IEEE 802.22 working group is to create a standardised air interface that exploits techniques derived from CR. Various studies [10], [11] indicate that large portions of the radio frequency spectrum are vastly under-utilised, especially in the TV bands. Thus far the SU has been assumed to be an opportunistic user, who continuously senses various unoccupied portions of the spectrum. These portions of the spectrum are then dynamically utilised. The SU later vacates the spectrum, so as to ensure that it does not interfere with the PU. This standard therefore deals with the opportunistic spectrum utilisation of existing TV bands in a manner that is non-interfering with current TV broadcasters, who possess the required licenses to operate in this particular band (also referred to as PUs) [12].

A. *Key characteristics*

The IEEE 802.22 WRAN standard has not yet been finalised and is still under development in the IEEE 802 LAN/MAN standards committee. Issues pertaining to both the physical and media access control (MAC) layers, as well as basic cognitive radio functionality, are discussed. Basic requirements for dynamic spectrum management and spectrum sensing are outlined. In Table I, the key physical layer parameters of the standard are summarised [13].

The standard assumes that CR will operate within the existing very high frequency (VHF) and ultra high frequency (UHF) licensed TV bands. Channel bandwidths for 6 MHz, 7 MHz and 8 MHz channels are catered for. In Southern Africa, analogue broadcast television systems currently fall under the international telecommunications union (ITU) PAL-I identification system. This system specifies an 8 MHz channel bandwidth. Spectrum sensing functionality is provided for as one of the mandatory features of the IEEE 802.22 standard. Provision has been made both for base stations and customer-provided equipment to perform spectrum sensing of three different signal transmission types. These include: analogue television transmissions, digital television transmissions and other licensed low power devices, e.g. wireless microphones. The standard specifies that the antenna used for spectrum sensing must be mounted at least 10 m above ground, be situated outdoors, be kept clear of any obstructions and have a 0 dBi omnidirectional reference antenna gain.

In the standard, spectrum sensing ability is characterised by the following parameters: receiver sensitivity, channel detection time (maximum of 2 s), probability of detection (should be greater than 90%) and probability of false alarm (should be less than or equal to 10%). The receiver sensitivities for analogue and digital TV, for the minimum sensing time when energy detection is employed, are respectively specified as -94 dBm and -116 dBm [13].

Table I
KEY PARAMETERS FOR THE IEEE 802.22 DRAFT STANDARD.

Parameters	**Specifications**
Network type	WRAN
Air interface	OFDMA
Fast Fourier transform	Single mode (2084)
OFDMA channel profile	6, 7 and 8 MHz
Maximum data rate	23, 27, and 31 Mbps
Coverage	17-30 km
Operating frequency range	54-862 MHz (VHF/UHF)
Frame size	100 ms
Forward error correction	½ rate convolutional code
Adaptive modulation schemes	BPSK, QPSK, 16-QAM and 64-QAM

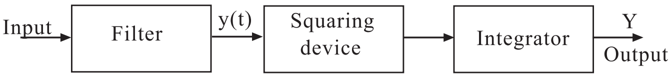

Figure 1. Energy detection.

III. SPECTRUM SENSING: ENERGY DETECTION

Amongst others, three widely used spectrum sensing methods are described in the literature [14], [15], viz. matched filtering, energy detection and cyclostationary feature detection. Among the three methods mentioned, energy detection has the lowest complexity and requires no prior information about the signal. However, a key trade-off of this scheme is its low sensing accuracy when compared to other methods. During the energy detection process, described in [16] (depicted in Fig. 1), the received signal is first pre-filtered by a band pass filter. The output of this filter is then squared and integrated over a time interval T to obtain some measure of the amount of energy contained within the received waveform. The output of the integrator, denoted by Y, is used to perform a detection test for a binary hypothesis where H_0 (the input is noise alone) and H_1 (the input is a signal plus noise) are tested for.

The probability of a detection (P_d) and the probability of a false alarm (P_{fa}) can be written as shown in Equation (1) and Equation (2), respectively,

$$P_d = P(Y > \lambda | H_1), \tag{1}$$

$$P_{fa} = P(Y > \lambda | H_0), \tag{2}$$

where λ is the decision threshold, when, for both H_0 (central chi-square distribution) and H_1 (non-central chi-square distribution), Y has a chi-square distribution. These distributions were chosen as they are commonly used to describe unknown deterministic signals [16]. After following the mathematical procedure discussed in [17], an equation relating the probability of a missed detection[1] (P_{md}) to the probability of a false alarm[2] P_{fa}, for a Rayleigh fading channel, can be written as,

$$\overline{P_{md\,Ray}}|_{u=1} = 1 - \exp\left[\frac{2\sigma^2 \ln P_{fa}}{2\sigma^2 + a\overline{\Upsilon}}\right], \tag{3}$$

where u refers to an even number of degrees of freedom, σ^2 is the variance, a is the non-centrality parameter of the distribution and $\overline{\Upsilon}$ is the average signal-to-noise ratio ($\Upsilon = \frac{E_s}{N_0}$, where E_s is the signal energy and N_0 is the one-sided power spectral density). To validate the theoretical expression in Equation (3), data was transmitted through a Rayleigh fading channel using the 2k mode of the digital video broadcasting – second generation terrestrial (DVB-T2) standard

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[1] The probability of a missed detection (P_{md}) is defined as the probability that a secondary user incorrectly assumes that a primary user is not in a specified band.

[2] The probability of a false alarm (P_{fa}) is defined as the probability that a secondary user incorrectly assumes that a primary user occupies a specified band.

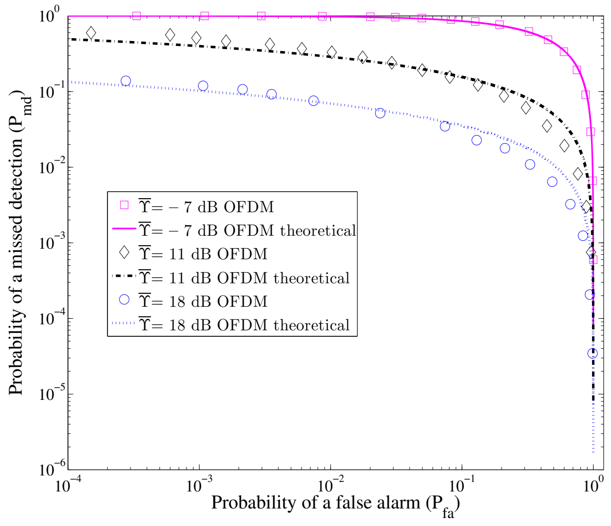

Figure 2. ROC comparison over a Rayleigh fading channel.

for a 16-ary quadrature amplitude modulated (QAM) Gray-coded orthogonal frequency division multiplexing (OFDM) constellation. For this DVB-T2 OFDM transmission, $\sigma^2 = 1$, $a = 2$ and $\delta = 2\sqrt{2}$. By using an energy detector the receiver operator characteristic (ROC) results, depicted in Fig. 2, offer a comparison between simulated and theoretical OFDM transmissions in a Rayleigh fading channel.
From these comparisons, a reasonably good correlation between the theoretically predicted and simulated results can be seen. The slight discrepancy between the theoretical and simulated results may be attributed to the fact that, in theory, the signal is assumed to have a non-centrality chi-square distribution. However, there is a slight difference between the assumed non-centrality chi-square distribution and the actual signal distribution. This indicates that Equation (3) can be used to determine the detection characteristics of a TV band. According to Fig. 2, it is also evident that in order to be within the IEEE 802.22 standard requirement (under Rayleigh fading conditions) that $P_{fa} \leq 0.1$ and $P_d \geq 0.9$ ($P_{md} = 1 - P_d = 1 - 0.9 = 0.1$), a $\overline{\Upsilon} \geq 11$ dB is required. Since $P_{fa} \approx 0.1$ and $P_{md} \approx 0.1$ for this particular case ($\overline{\Upsilon} = 11$ dB).

IV. PROACTIVE DYNAMIC SPECTRUM ACCESS

Once a SU has gathered enough information about its current environment (as prescribed in the IEEE 802.22 standard), through the energy detection process, it needs to determine whether to operate within a particular environment.

A. Model overview

When deciding where it should be operating, a SU needs to take into account the behaviour of the other users that currently occupy the surrounding spectral region. However, if the SU only makes that decision based on current information at time t, there will always be a possibility that the occupancy of the chosen channel will have changed by time $t = t + 1$. The SU will thus have made the wrong decision and will cause interference to the PU and be forced to change its decision. To avoid this problem, the concept of proactive channel switching has been proposed [6]–[8]. If the SU can obtain knowledge about PU behaviour before it actually happens, then it may base a proactive channel switching decision on this information. This process may thus be referred to as proactive dynamic spectrum allocation (PDSA).

Near future channel occupancy predictions will thus have to be made, in order for the SU to obtain this information. In this paper, a hidden Markov model (HMM) will be employed for this purpose, as described in [8], [18]. Using historical information, gathered during the spectrum sensing process, a two-state HMM was employed to predict near future channel occupancy. It should be noted however, that if the information obtained during the spectrum sensing process is inaccurate, the PU occupancy model will be incorrectly determined and the PDSA process will be adversely affected. It is thus important to perform spectrum sensing such that P_d will be maximised and subsequently P_{fa} minimised. In this paper, the method chosen for determining which channel would be most suitable to switch to, was based on the length of channel occupancy, i.e. out of a maximum channel set size of n the SU will try to determine the channel $Q = (q_1, q_2, \cdots, q_n)$, which will be most likely to remain unoccupied for the longest expected number of near future frame periods T_q, such that [7], [8],

$$Q = \arg\max_q T_q, \quad t + 1 \leq T_q \leq t + \rho, \tag{4}$$

where ρ denotes the number of near future predicted time slots employed in choosing the best channel. A simplified depiction of the PDSA process is provided in Fig. 3. The SU gathers information about its environment through a spectrum sensing operation, it then models this environment and predicts how it may change in the near future. Based on these predictions, a

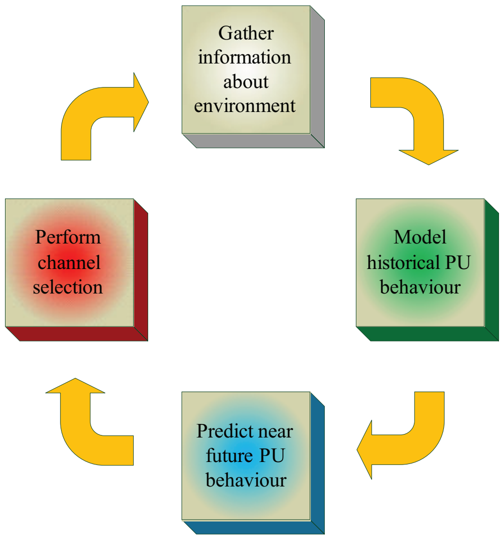

Figure 3. Simplified depiction of the PDSA process.

decision is then made as to which channel should be selected for use. This process is continuously repeated so that the SU can adapt to its environment as it changes.

B. Simulation results

Simulations were run to quantify the effect that PDSA has on DSA. For these simulations, it was assumed that the SU was operating within a generic UHF band, which has a very low percentage channel occupancy (spectrum measurements taken at the University of Pretoria indicate that this band is roughly only 23% utilised [19]). A set of simulated test data was thus generated in an attempt to recreate a similar spectrum utilisation scenario. A binary occupancy map of this data set is presented in Fig. 4, which represents ten predicted frequency channels for a range of 200 time slots of 10 ms each. The black areas represent the presence of a PU and the white areas portions of unoccupied spectrum.

The results presented in this section include plots that provide information about SU behaviour, specifically with regard to the effect that PDSA has on the channel switching process as the number of near future predicted time slots ρ, employed by Equation (4), is increased. These parameters were chosen due to their potential effect on SU throughput, SU power consumption and the number of disruptions experienced by PUs. In Fig. 5, a plot indicating the simulated number of channel switches required of a SU, over an incremental range of values for ρ, is provided. These results were generated from a set of available channels $\vartheta = [2, 4, \cdots, 10]$. A similar plot, indicating the required number of SU sensing operations, is provided in Fig. 6 (sensing operations were performed according to the aggressive approach described in [19]). It is evident that the required number of both channel switches and sensing operations decreases significantly as ϑ is increased. However, it would appear that once ϑ reaches eight channels, there is no longer any real benefit to further increasing ϑ.

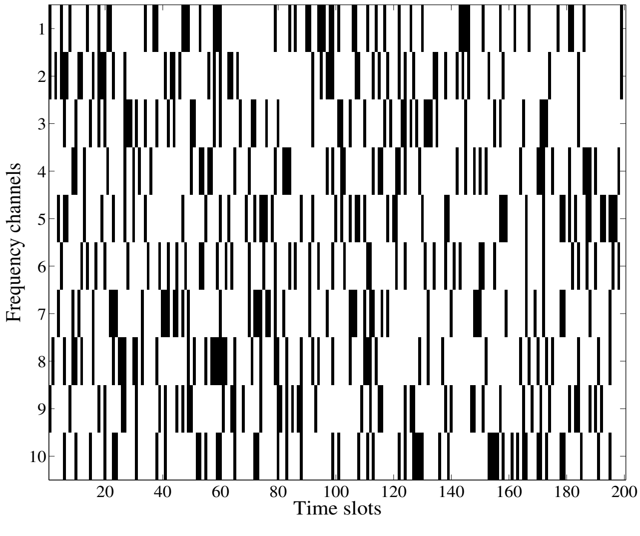

Figure 4. Channel occupancy matrix of simulated test data.

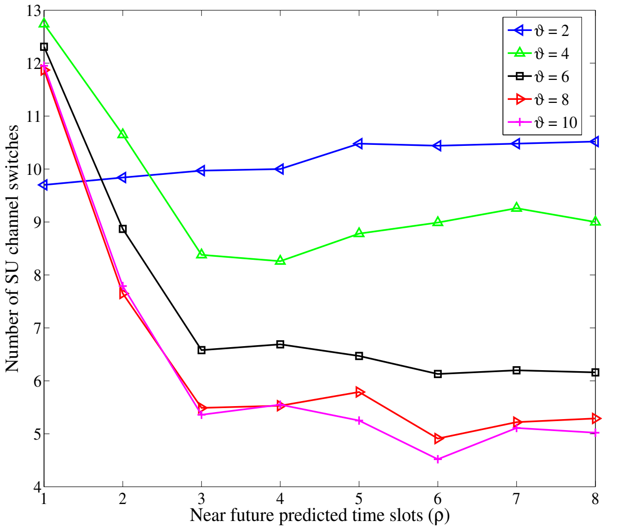

Figure 5. Number of required SU channel switches as ρ is increased for different numbers of available channels ϑ.

Predictions were made for the data presented in Fig. 4 and an overall prediction accuracy of approximately 65% was obtained. The effect that ρ has will depend on the accuracy of the near future channel occupancy predictions. The benefit of increasing ρ beyond a single future time slot is evident when evaluating Fig. 5 and Fig. 6. However, it would also appear that once $\rho > 5$, no further benefit can be derived from increasing ρ. It is also observed that the value chosen for ρ does not seem to be of any significance when ϑ is small, e.g. when $\vartheta = 2$, the SU does not have enough channels to choose from for the size of ρ to make any significant difference.

It would thus appear that an optimal PDSA point occurs for the combination of $\vartheta = 8$ and $\rho = 5$. However, apart from the prediction accuracy, this optimal point may well be influenced by the traffic density of the data set being examined.

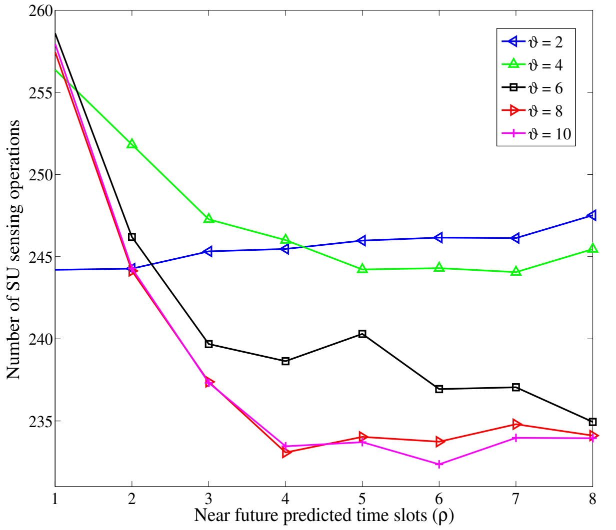

Figure 6. Number of required SU spectrum sensing events as ρ is increased for different numbers of available channels ϑ.

V. CONCLUSION

This paper described a theoretical closed form relationship between the probability of a missed detection and the probability of a false alarm for an unknown deterministic signal. Thereafter, by using energy detection, the ROC results were generated. These results suggested that an SNR value of more than 11 dB would be required, under Rayleigh fading channel conditions, for the spectrum sensing process to conform to the detection characteristics imposed by the IEEE 802.22 standard. In this paper, based on the spectrum sensing results, a proactive approach to dynamic spectrum access was employed where channel switching decisions were based on near future channel occupancy predictions. Results indicated that increasing the number of channels available to the SU, as well as the number of predicted near future time slots, to an optimal point (employed to choose which channel to operate within), significantly improves the channel allocation process. The point where $\vartheta = 8$ and $\rho = 5$, was determined to be the optimal point for the spectrum occupancy characteristics simulated in this paper.

Future work may include examining how the optimal point may change under different spectrum occupancy conditions.

VI. ACKNOWLEDGMENT

This research is supported by the Sentech Chair in Broadband Wireless Mobile Communications (BWMC) and the National Research Foundation (NRF) of South Africa.

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