International Journal of Engineering and Technology Innovation, vol. 7, no. 2, 2017, pp. 98 - 116

Two Heterogeneous Channel Assembling Strategies in Cognitive Radio Networks: a Performance Analysis

Ebenezer Esenogho*, Viranjay M. Srivastava

School of Electrical, Electronic and Computer Engineering University of KwaZulu-Natal, Durban, South Africa.

Received 06 August 2016; received in revised form 24 October 2016; accepted 10 November 2016

Abstract

To maximize the spectrum hole (TV white space), a robust channel allocation policy featuring aggregation of several primary user idle resources (TVWS) into groups of useable secondary channels has been studied in literatures. However, to be applied in real world, the channel assembling strategies (CAS) must consider the factors that affect the quality and capacity of the available channels. This includes the dynamic wireless link, the signal to noise ratio, traffic class and enabling technique like adaptive modulation and coding (AMC). These make the strategies heterogeneous and robust. Motivated by this, we proposed two CAS called Immediate Blocking Strategy (IBS) and the Readjustment Based Strategy (RBS) that consider the heterogeneity of a wireless channel. An analytical framework to evaluate the performance of the strategies is developed. An investigation of the proposed CAS has shown to improve the secondary user (SU) performance in terms of capacity, blocking, forced termination (FT) and acceptance/admission probabilities respectively, depending on the system parameters selected. The investigation was validated by extensive system simulation.

Keywords: AMC, channel assembling (CA), cognitive radio networks, heterogeneous, signal to noise ratio

1. Introduction

Cognitive radio (CR) is an agile technology for supporting dynamic spectrum access and allocation [1-2]. This is embedded in its capability to adaptively and independently adjust its transmission parameters and learn from its previous experience [3-5]. The channels used by the secondary users (cognitive users) are originally owned by the primary user (PU) the licensed owner. However, the PU utilizes its channels in an alternating manner there by creating spectrum holes (idle channels). The secondary user (SU) opportunistically utilizes these idle channels and vacate when the PU arrives to avoid interference, thus taking advantage of the PU's ON/OFF behaviour. These unused/idle PU channels (spectrum holes) need coordination in other to boost SU throughput and as such, the need for channel assembling. CAS enables SUs to combine several idle channels to optimize its performance. This has been shown in terms of high data rate, low blocking, forced termination and spectrum utilization of the secondary network [6-7]. The core task of CR can be summarized into spectrum sensing, spectrum management, and spectrum sharing and spectrum adaptation. As a focus, spectrum adaptation is the adjusting of SU channels upwards or downwards depending on PU events (arrival/departure). The performance of cognitive radio networks (CRN) requires a robust channel management/allocation techniques and one form of which is a dynamic resource allocation strategy which allows the combination of scattered spectrum holes into one logic usable SU channel. CAS improves SU performance, especially when spectrum adaptation is implemented with the right parameters [7-9]. Since next generation wireless networks like 5G is proposed to support multimedia applications with diverse resource requirements, efficient channel assembly strategies are required in CRN so as to improve SU throughput. The number of channels assembled for the strategies depends

---

* Corresponding Author E-mail: ebenic4real@gmail.com

on the following factors which includes the PU behaviour, the dynamics of the wireless link, and AMC. Aggregating channel is possible and convenient under certain PU activity patterns with several of them modelled as Markovian process. Although other models exist, vary in their ON/OFF distribution [10-11]. For CAS to be effective and implementable, it must take into account the PU behavioural pattern as investigated in [12], the signal to noise ratio (SNR) per frame and the slot by slot utilization. These factors determine the number of channels available, the bit error rate (BER) and packet error rate (PER) of the transmission. A realistic and dynamic wireless channel could be represented by several finite states [13]. For instance, a three state wireless link for a SU could be of good, moderate and bad quality respectively. This is a more practical scenario of a varying wireless link as opposed to novel homogeneous case study in [6-7]. Therefore, an efficient CAS must take into account the dynamics of the wireless link, the SU of different traffic classes and dynamic modulation scheme this forms the bases of this current study. Different techniques have been proposed to mitigate various impairments of the wireless communication system. AMC is one of those technologies that have significantly improved the spectrum usage by classifying the modulation scheme, spectral efficiency and code rate [14]. Also, it optimizes the rate at which unit of information (bit or packet) are sent with targeted error rates [15]. The varying SNR introduce the multi rate capacities of wireless links in terms of the number of channel slot used, as opposed to the constant homogeneous single rate systems [6]. Optimal CAS should consider this dynamism with AMC and it is upon this premise that we have proposed and investigated CAS. This paper proposed two CAS that considered the dynamic wireless link, the effect of signal to noise ratio, the diversity of the SU traffic class and AMC. Furthermore, this paper develops an analytical framework to evaluate the performance of the proposed CAS utilized in this work. The rest of the paper is organized as follows: Section 2 summarizes related works; the system model of the proposed strategy is presented in Section 3. Wireless resource capacity modelling is founded in Section 4 while CAS is discussed in Section 5. An analytical system model is presented in Section 6 while, Section 7 captures the numerical result with the corresponding discussion. Finally, this paper is concluded in Section 8.

2. Related Works

Several CAS have been proposed in literature in an attempt to analyse the performance of CRN. However, all of which can be broadly classified as static or dynamic. In static channel assembling, a SU can aggregate a fixed number of primary channels, while in dynamic; a SU can aggregate a variable number of channels. In [7], an analytical model for CRNs with spectrum adaptation was developed. In their study, two representative CAS that consider spectrum adaptation with a heterogeneous traffic were proposed. The performance of these strategies is analysed based on the proposed Continuous Time Markov Chain (CTMC) models. In [8], an expression for the theoretical capacity upper bound of the secondary network with CA was proposed. Their investigation shows that the PUs sporadically appear with services far longer compared with SU services. In [16], two channel assembling scheme for wideband CRN where proposed which are a constant channel assembling scheme and a variable channel assembling scheme. In the variable channel assembling scheme, the bandwidth of the SU is assembling with a probability distribution on the basis of the number of the residual channels. In [17], the performance analysis of two CAS with imperfect sensing for wideband CRNs were proposed just like in [16], a constant channel assembling (CCA) scheme and a variable channel assembling (VCA) scheme. The difference is that imperfect sensing was considered in their work. In [18], the performance comparisons of CAS were studied when spectrum adaptation was not implemented. In their work, three scenarios were considered: without channel assembling, with a fixed number of assembled channels and assembling all idle channels (greedy approach) when SU services access the networks. In [19], an analytical model for a wideband CRN, where an SU assembles multiple primary channels with spectrum handover was presented. In their work, characteristics of imperfect signal detection mechanism were considered. In [20], CA for elastic traffic with channel adaptation was studied depending on channel availability and other SU activities. Closely related works are found in [6-7] and [21- 22]. [6-7] implement a dynamic CAS for heterogeneous traffic with spectrum adaptation, employing channel sharing and spectrum handover. In these studies, the authors assumed that the SU service will experience stable services without the effects of channel fading through advanced underlying physical layer techniques. However, some key physical layer parameters like varying SNR and AMC which have a great effect on the performance of any CAS in CRNs were not considered in their investigations. Attempt were made to considered these parameters in [21-22] but without detailed analytical frame work. Due to frequent blocking and dropping of SU services, the queuing based CAS has gained importance. [23] incorporates a queuing regime into CAS of [7] such that when there are insufficient spectrum resources, like an open network model (lossy system), where a new secondary user request is blocked and the interrupted services are dropped, it is instead queued and served later. This reduces the blocking and forced termination (FT) probability respectively, of the SU services while increasing the network capacity and improving spectrum utilization. [23-24] combine queuing based CA and channel fragmentation (CF) strategies. In their proposal, SU dynamically splits it currently occupied channel into finer granules in others to accommodate new arrivals. The pre-empted SUs are queued pending when available channels reappear or a pre-determined maximum queuing time expires. The effect of introducing a finite queue regime is to reduce blocking of SU request and avoiding FT of SU services respectively. Despite the tremendous effort on CA in CRNs, previous studies did not vividly and explicitly consider in details the dynamics (varying nature) of the wireless link especially a three state scenarios and the effect of a mitigating technique like AMC, which this study considered.

3. System Model

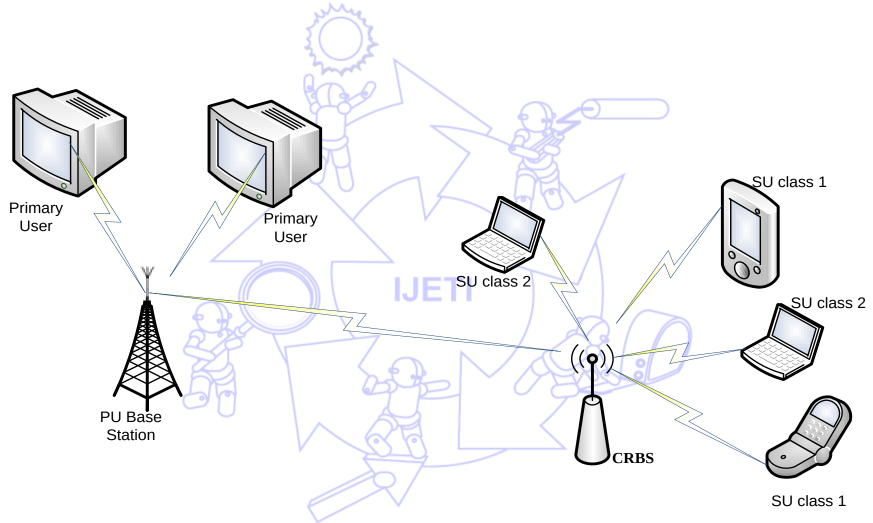

Fig. 1 Network architecture

The system model is an infrastructure based network model consisting of a PU base station (PUBS), a cognitive radio base station (CRBS) and their associate users respectively, operating in the same frequency band as shown in Fig. 1.

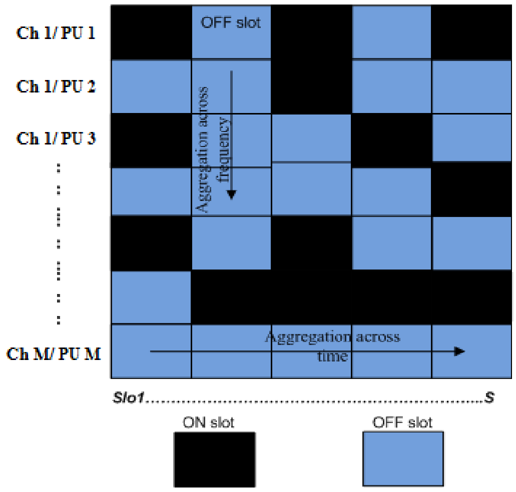

Fig. 2 Illustration of wireless frame utilization with OFDMA scheme

The PU, being the licensed user, has full priority to utilize the spectrum and can pre-empt the SUs at any time irrespective of the classes. The PU requires one channel whereas a SU requires/aggregates sub-channels both in the time and frequency domains using the Orthogonal Frequency Division Multiple Access (OFDMA) scheme [25], as shown in Fig. 2. A SU opportunistically utilizes the PU's channels and employs any of the CAS proposed. The licensed band is composed of ω PUs with M channels, where ω and M are positive integers. The CRBS help the SU to structure the channels into slots (frames) and resource utilization per channel per frame becomes on a mini-slot basis for SUs. The PU operates the channels on an ON/OFF basis while the SU opportunistically assembles multiple adjacent or non-adjacent mini-slots in coherent time intervals.

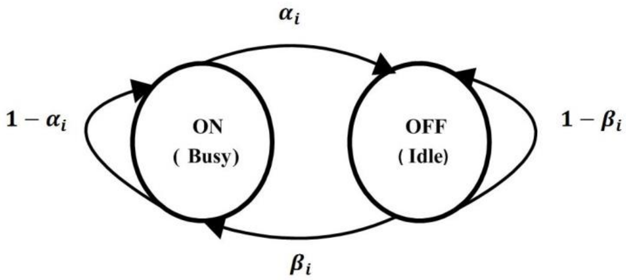

Fig. 3 The PU ON-OFF channel usage pattern

The channel frame utilization map for a given PU ON/OFF behaviour is shown in Fig. 2 and Fig. 3, respectively. The channel state utilization of PU is characterized by two state Markov chain of Fig. 3 with α_i, being the transitional probability from ON state to OFF state and β_i being the transitional probability from the OFF state to the ON state for the i-th channel. For the SUs, the CRBS sense (we assumed perfect sensing) different SNRs since all SUs cannot be homogeneous. Therefore, we assume the SU's SNRs will either fall under good, moderate or bad SNR (channel condition). This dynamic results in a heterogeneous system with variable channel slot capacity such that SU traffic requires a particular transmission rate/number of mini-slot for a particular channel condition.

4. Wireless Resource Capacity

4.1. *SU Wireless Channel Model and AMC*

The Nakagami-m channel model is used to describe the wireless link due to its versatility of spanning a wide range of fading channels [26-27]. The channel quality is captured by the received SNR γ. The different channel conditions are captured by the finite state Markov chain (FSMC) whose analysis for slow fading channel conditions is well known [15]. On the physical layer, AMC is used in maximizing data rate and adapting transmission parameters in accordance to the channel state, thus maintaining a prescribed PER with high spectral efficiency [14-15]. However, the PER in the occurrence of additive white Gaussian noise (AWGN), is presented in [26]. The numbers of channel-slots a SU assembles to use for data transmission decreases with an increase in mode and received SNR. For the SUs, we assume Mode 1 corresponds to quadrature phase shift keying (QPSK) and represents bad channel condition (bad SNR), Mode 2 corresponds to 16-quadrature amplitude modulation (QAM) and represents moderate channel condition (moderate SNR), while Mode 3 corresponds to 64-quadrature amplitude modulation (QAM) and denotes a good channel condition (good SNR), as shown in Table I. The mode is chosen in a way to maintain a particular PER for the wireless conditions. [25-27]

4.2. *AMC and SU Frame configuration*

Let the received SNR per frame, γ, be a gamma distributed random variables. Let the entire range be partitioned into $N+1$, threshold's such that $\Gamma_n \in [\,\gamma_n\,,\ \gamma_{n+1}..]$ where $\Gamma_0 = 0$ and $\Gamma_{N+1} = \infty$. The mode n will be chosen with a probability [4, eq.[28]. γ_n is the instantaneous SNR at a particular mode n. Let the packet length in bits be denoted by $\emptyset$ and R_n be the number of bits carried per symbol for mode n. where the mode ranges $1 \le n \le N$. The number of channel slots in a fixed frame S is a variable function of the dynamic SNR. The number of slots S, in a frame for a coherent time interval is a variable function of the dynamic SNR (γ). It can be expressed as [29].

$$S = \left(\frac{\emptyset}{R_n \varepsilon_s R_s}\right) \cdot R_N \tag{1}$$

where ε_s is the channel constant and R_s , R_N denotes the symbol rate per send and the highest transmission mode respectively.

4.3. SU Mini-Slot Configuration

The number of mini-slots assembled for a SU decreases with increase in received SNR quality (as the SNR become better) as capture in Table 1. θ_n is the number of slots a SU can assemble or aggregate in a given mode n or SNR. In our notations, N denotes the highest mode, n denotes the n^{th} mode. From Table 1, the number of SU mini-slots is given by

$$\theta_n = \begin{cases} \underbrace{\begin{matrix} \frac{R_N}{R_n} = 1 & n = N \\ 0 \quad n = 1, \ . \ .N-1 & \end{matrix}}_{number\ of\ slots\ allocated\ in\ good\ SNR} \\ \underbrace{\begin{matrix} 0 & n = N \\ \frac{R_N}{R_n} & n = 1, \ . \ .N-1 \end{matrix}}_{number\ of\ slots\ for\ moderate, bad\ channel\ state} \end{cases} \tag{2}$$

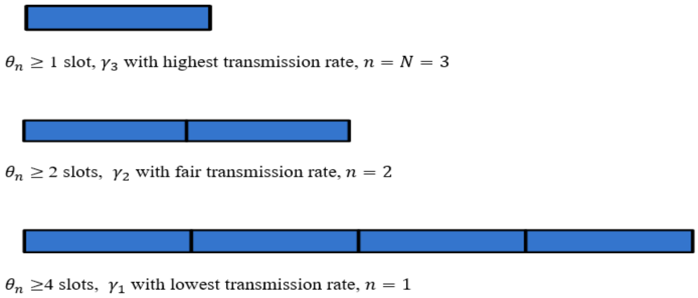

Fig. 4 Mini-slot configuration as a function of SNR (γ)

The uniqueness of this strategies is that in the highest mode where $n = N$ (good SNR), SUs will aggregate few slots in order to accommodate more SUs. However, as the channel condition deteriorates, more slots will be needed to meet the SU's QoS requirements.

Table 1 Transmission Modes with Convolutionally Coded Modulation [30], [31]

(n) AMC mode	Modulation Scheme	Capacity (Mbps)	Spectral Eff. (R) bit/s/Hz	SNR (γ)dB	Code Rate (r)
1	QPSK	3.74	0.624	4.3	1/2
2	16-QAM	7.49	1.248	10.2	3/4
3	64-QAM	14.98	2.496	18.3	2/3

The total capacity of the system is given by $(M * S)$ while the channel utilization is given as $\delta_i = \beta_i / (\beta_i + \alpha_i)$ ratio. Therefore, The PU's channel slot capacity θ_{pu}, is given as

$$\theta_{Pu} = S.\sum_{i=1}^{M}\left(\frac{\beta_i}{\beta_i + \alpha_i}\right) \tag{3}$$

$$\theta_{Pu} = S.\sum_{i=1}^{M} \delta_i \tag{4}$$

while SU channel slot capacity θ_{su} is the reminder after PU occupancy. It can be expressed as

$$\theta_{su} = (M * S) - \theta_{Pu} \tag{5}$$

5. Channel Assembling Strategies

As mentioned previously, two CAS are proposed. They are Immediate Blocking Strategy (IBS) and the Readjustment Based Strategy (RBS). In the IBS, the SUs are immediately blocked if there are insufficient or no resources. In the RBS, the SU channel slots are adjusted (upward or downward) to reduce blocking and forced termination when a PU arrives and also accommodate new SU arrivals. The details are discussed in the subsections that follow.

5.1. *Immediate Blocking Strategy* $(\omega, \theta_{su}, \theta_{n_i})$

In IBS, when there is no capacity upon SU request for resources (channel slots) irrespective of the SNR, the SU is immediately blocked. This implies that for a given wireless link condition (good, moderate or bad SNRs) the CRBS assemble a given number of channel slots based on the SNR. However, if a PU arrives and selects from the allocated resources, and there are not enough idle channel slots to make up for the depletion, then the SU is forced to terminate [21], [22]. Let V_n be the total number of SUs in the system and the resource requirements be θ_n which could be (θ_g, θ_m or θ_b). The SU will be admitted or accepted if the condition in (6) is satisfied.

$$\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}, \quad \forall\, z(\phi) < M * S \tag{6}$$

Else, the SU is blocked if satisfies the equation (7) which is a reverse of (6).

$$\theta_{su} \leq \sum_{i=1}^{V_n} \theta_{n_i}, \quad \forall \{M * S - z(\phi)\} < \quad \theta_{ni} \tag{7}$$

with M being the number of channels, an SU can be forced to terminate if the arriving PU finds the SU utilizing one of its channel slots and there are no free slot(s). That is, if equation (8) is satisfied. Note the conditions for blocking and forced termination are similar. The only difference is that in forced termination, the SU would have been accepted/admitted into the spectrum. It can be expressed as

$$\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}, \quad \forall \{M * S = z(\phi)\} \tag{8}$$

This implies a reduction in the number of admitted SU resources. Similarly, an arriving PU could be blocked if condition (9) is satisfied.

$$\omega \geq M \tag{9}$$

However, since PU is given high priority, we are not considering PU blocking and did not look at this condition because is it not our focus although it is possible among PUs of different classes. However, the CRBS executes IBS in algorithm I below.

Algorithm I for the CA using IBS

// SU arrival

```
CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link state (SNR) for SUs.
   CRBS check $\theta_{su}$; // cognitive radio base station checks available recourse for SUs
If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}$); // resource assembly test as a function of SNR/mode pair.
     $SU_i$_admit = true; //admit $SU_i$ and assembles
Else
     $SU_i$_admit=false; //block the $SU_s$
Else
   End if ; // terminate if no event
```

```
// PU arrival
CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link state (SNR) for SUs.
If [($\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}$) ]; // PU arrival pick some SU resources
    $SU_i$_drop =true; // forced-terminate of ongoing $SU_s$
  Else
End if ; // terminate if no event
// PU departure
  CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link for PU absence
If $PU_{i\_}$channel-slots=idle (free); // free PU slots
    $SU_i$_admit = true; // admit new $SU_s$
End; // end the process if no other events
Go to start; // repeat the process if need arise since it is a close loop system
```

5.2 Readjustment Based Strategy ($\omega, \theta_{su}, \theta_n^{min}, \theta_n^{max}$)

In this strategy, secondary user needs a minimum of θ_n^{min} and maximum of θ_n^{max} resources to commence service and stop assembling respectively. When a secondary user requests for service, the assembling protocol domiciled in the CRBS checks for resource accessibility similar to the IBS scheme. If the resources (channel slot) are available and adequate, the secondary user is granted access. Else, if otherwise as a consequent of PU appearance, the readjustment algorithm II is executed which enables the SU with the maximum assembled channel denote to starving or new arriving SUs respectively.

Algorithm II for the CA using RBS

```
//SU arrival
CRBS check wireless link $\gamma_{su}$ ; // cognitive radio base station checks wireless link state (SNR) for SUs.
        CRBS check $\theta_{su}$ ; // cognitive radio base station checks available recourse for SU
          If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}^{min}$ ); // test for $SU_i$ resources
        $SU_i$_admit = true; // admit $SU_i$ and assemble
Else
        if ($\sum_{i=1}^{V_n} \theta_{n_i}^{min}$) < $\theta_{n,new}^{min}$)] ; // test for new SU arrival due to PU arrival
Go to Do procedure; // Next three step below
// PU arrival
CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link state (SNR) for SUs.
if ( $\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}^{min}$); // PU arrives and pick some SU resources
Do $(\theta_j^{max} - 1)$, ++ j; // SU with max. channel, donate and iterate over j user resources
   $SU_{i,j}$,_admit = true; // admit $SU_{i,j}$ and assemble for both users
      Else
          $SU_i$_admit =false; // block new $SU_i$ due to no-free slot or insufficient
          If all conditions cannot be met
        $SU_i$_ FT =true; // force-terminate ongoing $SU_i$
End if; // start the process.
// PU departure
CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link for PU absence
```

```
If $PU_{i\_}$channel-slots=idle; // free channel slot exists
    $SU_i$_admit = true; // admit $SU_s$ admit $SU_i$ and assemble
  Do $(\theta_j^{min} + 1)$; // $SU$ with min channel adjust upward
End; // end the process if no other events
Go to start; // repeat the process if need arise since it is a close loop system
```

6. System Model Analysis

6.1. System Analytical Models

The system features static and dynamic SU traffic that employs the CAS of Section 5. The resource requirement for the static traffic is θ_n while the dynamic user is bounded between θ_n^{min} and θ_n^{max} (lower and upper limit). The arrival rate for the PUs and SUs follows a Poisson distribution with parameters λ_p and λ_s for PUs and SUs respectively. The service times are exponentially distributed with the service rates μ_p and μ_s for the PUs and SUs respectively. As in [6-7], the total service for a user is assumed to be the product of the user channel slot service rate and the number of assembled channel slots $\theta_{su}\mu_{su}$. The system can be modelled as a CTMC with state represented by $\phi = \{\omega, V_g, V_m, V_b\}$ where ω is the number of PUs, V_g is the number of SUs in a good state, V_m is the number of SUs in a moderate state, and V_b is the number of SUs in a bad state in the system respectively. The utilization is expressed as

$$z(\phi) = \omega + (\theta_g V_g + \theta_m V_m + \theta_b V_b) \tag{10}$$

where θ_g, θ_m, and θ_b are the number of channel slots assembled by the CRBS for its associate SUs with respective wireless links. The system transition diagram is shown in Fig. 5.

In Fig. 5, the transitions can be characterized as *internal (horizontal)* and *external (vertical)*. The internal transition occurs among SUs within the system (admitted SU) and their transitions are a function of the varying wireless link and other factors mentioned previously. The external transition occurs as a result of arrival or departure of new PUs/SUs into the system. Admission or blocking occurs at the point of entrance into the system, while forced termination occurs for already admitted/accepted SUs.

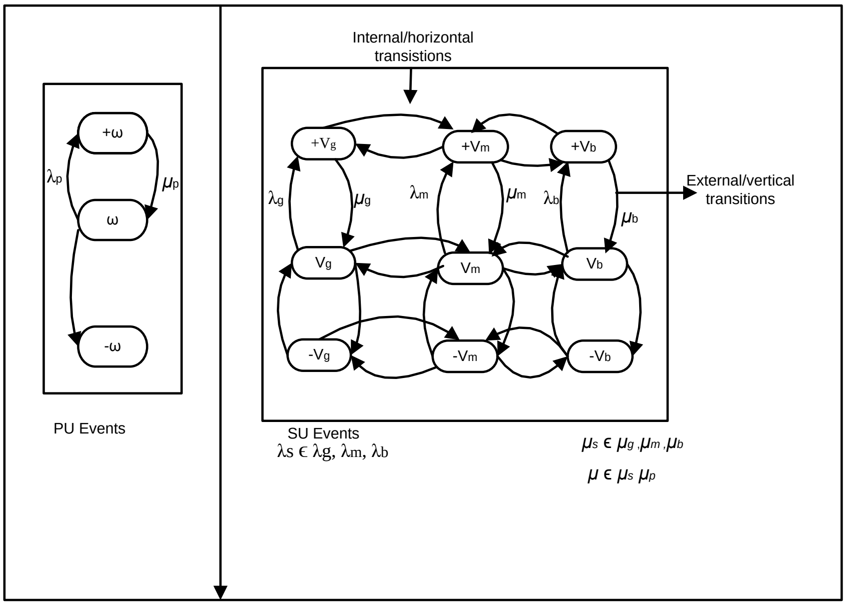

Fig. 5 System Transition Diagram

6.2. CTMC Analysis for IBS

The possible feasible state of the strategy is expressed as ɋ $= \{\phi \mid \omega, V_g, V_m, V_b) \geq 0;\ z(\phi) \leq M * S\}$. Subsequently, we describe all the possible state transition of the system. However, for simplicity, the PU is assumed either departing/arriving ($\omega - 1 or\ \omega + 1$). Hence, the transition table (ω, V_g, V_m, V_b) reflects more of the SUs state events which are our utmost concern. Note: crossing of state (good to bad or vice versa) is not allowed as shown in Fig. 5, since we are considering slow fading.

6.3. Performance Measures for IBS

These derivations are based on the premise of [6-7]. However, in this paper, three channel conditions were considered for the SUs. The blocking, FT and admission/acceptance probabilities respectively, are also considered based on the different channel conditions. The state transitions are summarized in Table 2. Based on the transition rates for the three channel states, the balanced equation and the normalized equation can be established in eq. (11). $\boldsymbol{\psi}$ is the transition rate matrix while the state probabilities are denoted by $\pi(\phi)$ thus, the probability of state ϕ can be obtained. Given the state probabilities $\pi(\phi)$, the systemperformance can be developed as follows.

$$\pi\boldsymbol{\psi} = 0, \qquad \sum_{\phi \in ɋ} \pi(\phi) = 1 \tag{11}$$

Table 2 Transition state table for the IBS Strategies $(\omega, \theta_{su},\ \theta_n\ )$

No.	Present State	Next state	Possible State Events	Transition Rate
	(ω, V_g, V_m, V_b)	PU departs/arrival		
(1)		$(\omega - 1, V_g, V_m, V_b)$	PU departs from the system.	$\omega\mu_p$
(2)		$(\omega + 1, V_g, V_m, V_b)$	PU arrives into the system.	λ_p
		SU departs/arrival		
(3)		$(V_g - 1, V_m, V_b)$ (external)	SU in good state departs from the system after service completion.	$[\mu_s V_g]$
(4)		$(V_g - 1, V_m + 1, V_b)$ (internal)	SU transits from good to moderate state.	$\left[\frac{\theta_m V_m}{z(\phi)}\right]\lambda_s$
			SU in a moderate state departs after service completion.	$[\mu_s V_m]$
			SU in a moderate state FT due to PU arrival.	$\left[\frac{\theta_m V_m}{z(\phi) - \omega}\right]\lambda_p$
(5)		$(V_g + 1, V_m, V_b)$ (external)	SU arrives into the system in good state with the likelihood of being admitted/accepted, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_g} \theta_{g_i}$) of the channel slot required by the V_g, i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}, \forall\ z(\phi) < M * S$ as in equation (6)	$\left[\frac{\theta_g V_g}{z(\phi)}\right]\lambda_s$
			Otherwise, it is blocked which denotes NOT accepted i.e. if $\theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i},\ \forall\{M * S - z(\phi)\} < \theta_{g_i}$ as in equation (7)	
			No FT occurred in this event i.e. FT = 0 (PU absent)	FT = 0
(6)		$(V_g + 1, V_m - 1, V_b)$ (internal)	SU transits from a moderate state to good state.	$\left[\frac{\theta_g V_g}{z(\phi)}\right]\lambda_s$
			SU in a good state departs after service completion.	$[\mu_s V_g]$
			SU in a good state FT due to PU arrival with rate.	$\left[\frac{\theta_g V_g}{z(\phi) - \omega}\right]\lambda_p$
(7)		$(V_g, V_m, V_b - 1)$ (external)	SU in a bad state depart from the system.	$[\mu_s V_b]$
(8≡4)		$(V_g, V_m + 1, V_b - 1)$ (internal)	SU transits from a bad state to a moderate state.	Same as (4)
			SU in a moderate state departs after service completion.	Same as (4)
			SU in a moderate state FT due to PU arrival	Same as (4)

Table 2 Transition state table for the IBS Strategies $(\omega, \theta_{su}, \theta_n)$ (continued)

No.	Present State	Next state	Possible State Events	Transition Rate
(9)		$(V_g, V_m, V_b + 1)$ (external)	SU arrives into the system in bad state with the likelihood of being admitted/accepted, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_b} \theta_b$) of the channel slot required by the V_b, i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b} \theta_{b_i}, \forall\, z(\phi) < M * S$ as in equation (6)	$\left[\frac{\theta_b V_b}{z(\phi)}\right] \lambda_s$
			Otherwise, it is blocked which denotes NOT accepted i.e. if $\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}, \forall\{M * S - z(\phi)\} < \theta_{b_i}$ as in equation (7)	
			No FT occurs in this event i.e. $FT = 0$	FT = 0
(10)		$(V_g, V_m - 1, V_b + 1)$ (internal)	SU transits from a moderate to a bad state.	$\left[\frac{\theta_b V_b}{z(\phi)}\right] \lambda_s$
			SU in moderate state depart after service completion.	$[\mu_s V_b]$
			SU in moderate state FT due to PU.	$\left[\frac{\theta_b V_b}{z(\phi) - \omega}\right] \lambda_p$
(11)		$(V_g, V_m - 1, V_b)$ (external)	SU in moderate state depart from the system.	$[\mu_s V_m]$
(12)		$(V_g, V_m + 1, V_b)$ (external)	SU arrives into the system in moderate state with the likelihood of being admitted/accepted, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_m} \theta_m$) of the channel slot required by the V_b, i.e. if $\theta_{su} \geq \sum_{i=1}^{V_m} \theta_{m_i}, \forall\, z(\phi) < M * S$ as in equation (6)	$\left[\frac{\theta_m V_m}{z(\phi)}\right] \lambda_s$
			Otherwise, it is blocked which denotes NOT accepted i.e. if $\theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}, \forall\{M * S - z(\phi)\} < \theta_{m_i}$ as in equation (7)	
			No FT occurs in this event i.e. FT = 0 (PU absent)	FT = 0

(a) *The Blocking Probability*, P_b^n

In this work, blocking probability is expressed in rates. However, the blocking probability P_b^n at a particular channel state (good, moderate or bad) is the sum of all probabilities of states that cannot admit/accept SU into the system. The arriving SU will be blocked if the sum of the available idle channels/slots is less than the required, as stated in the table. It can be expressed as

$$P_b^n = \frac{Total\ SU\ blocking\ rate\ at\ a\ particular\ channel\ state}{SU\ arrival\ rate\ at\ a\ particular\ channel\ state} \tag{12}$$

$$P_b^g = \left[\sum_{\phi \in ς} \frac{\theta_g V_g}{z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi \in ς} \frac{\theta_g V_g}{z(\phi)} \pi(\phi)\right], \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}, M * S - z(\phi) < \theta_g \tag{13}$$

where P_b^g is the blocking probability when the wireless link is in good state.

$$P_b^m = \left[\sum_{\phi \in ς} \frac{\theta_m V_m}{z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi \in ς} \frac{\theta_m V_m}{z(\phi)} \pi(\phi)\right], \theta_{su} \leq \sum_{i=1}^{V_m} \theta_{m_i}, M * S - z(\phi) < \theta_m \tag{14}$$

where P_b^m is the blocking probability when the wireless link is in moderate state.

$$P_b^b = \left[\sum_{\phi \in ς} \frac{\theta_b V_b}{z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi \in ς} \frac{\theta_b V_b}{z(\phi)} \pi(\phi)\right], \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}, M * S - z(\phi) < \theta_b \tag{15}$$

where P_b^b is the blocking probability when the wireless link is in bad state.

(*b*) *The forced termination probability,* P_{ft}^{n}

The forced termination occurs whenever an ongoing SU service is interrupted by a PU arrival. This is regardless of the wireless channel state and the SU, which cannot hands-off to idle channels. In this work, FT probability denotes the total FT rate divided by the total admitted/accepted SU rate. It can be expressed as

$$P_{ft}^{n} = \frac{Total\ SU\ FT\ rate\ at\ a\ particular\ channel\ state}{SU\ connections\ (rate\ of\ commensed\ SU\ service)} \tag{16}$$

However, SU connections rate/rate of commenced SU service indicates that admittance has been granted. This can be expressed as $(1-P_b^n)\lambda_s$. Hence,

$$P_{ft}^{g} = \left[\lambda_p \sum_{\phi\in \text{₵}} \frac{\theta_g V_g}{Z(\phi)-\omega}\,\pi(\phi)\right] \Big/ (1-P_b^g)\lambda_s = \frac{\lambda_p}{(1-P_b^g)\lambda_s}\left[\sum_{\phi\in \text{₵}} \frac{\theta_g V_g}{Z(\phi)-\omega}\,\pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_g}\theta_{g_i}\ , M*S = z(\phi) \tag{17}$$

where P_{ft}^{g} is the FT probability when the wireless link is in good state.

$$P_{ft}^{m} = \left[\lambda_p \sum_{\phi\in \text{₵}} \frac{\theta_m V_m}{z(\phi)-\omega}\,\pi(\phi)\right] \Big/ (1-P_b^m)\lambda_s = \frac{\lambda_p}{(1-P_b^m)\lambda_s}\left[\sum_{\phi\in \text{₵}} \frac{\theta_m V_m}{Z(\phi)-\omega}\,\pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_m}\theta_{m_i}\ , M*S = z(\phi) \tag{18}$$

where P_{ft}^{m} is the FT probability when the wireless link is in moderate state.

$$P_{ft}^{b} = \left[\lambda_p \sum_{\phi\in \text{₵}} \frac{\theta_b V_b}{z(\phi)-\omega}\,\pi(\phi)\right] \Big/ (1-P_b^b)\lambda_s = \frac{\lambda_p}{(1-P_b^b)\lambda_s}\left[\sum_{\phi\in \text{₵}} \frac{\theta_b V_b}{z(\phi)-\omega}\,\pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_b}\theta_{b_i}\ , M*S = z(\phi) \tag{19}$$

where P_{ft}^{b} is the FT probability when the wireless link is in bad state

(*c*) *Acceptance/Admission probability,* P_a^n

The acceptance/admission probability is the probability that enough resources exist for the SU when it arrives. In other words, the residual resources (channel-slots) after PU occupancy are greater than or equal to the resources required by the SU. It can be expressed as the rate of *Not Blocked* with respect to the wireless link.

$$P_a^n = (1-P_b^n) \tag{20}$$

For each wireless link condition, it can be expressed respectively as follows

$$P_a^g = \left(1-P_b^g\right) \tag{21}$$

where P_a^g is the acceptance/admission probability when the wireless link is in good state.

$$P_a^m = (1-P_b^m) \tag{22}$$

P_a^m is the acceptance/admission probability when the wireless link is in moderate state.

$$P_a^b = (1-P_b^b) \tag{23}$$

(*d*) *Capacity,* σ_n

The capacity of the SU is the average service rate of the SUs. This implies the average number of SU completion per time. However, in this work, the capacity varies from one wireless condition to another since the number of channel slots assembled by the CRBS and the number of SUs in a particular wireless condition varies. For simplicity, it can be expressed as

$$\sigma_n = \sum_{\phi\in \text{₵}} \mu_s^n \theta_n\, V_n\, \pi(\phi) \tag{24}$$

Note that the generic symbols θ_n and V_n could not be used when representing blocking, FT and access/admission probability above because of their respective specificity (different criteria). Note, $\theta_n \equiv \theta_g, \theta_m$ or θ_b and $V_n \equiv V_g, V_m$ or V_b respectively. Also, $V_g, V_m, V_b \in V_n$ and $\theta_n, \theta_g, \theta_m, \theta_b, \theta_n^{min}, \theta_n^{max} \in, \theta_{su}$

(e) *Service rate, μ_s^n*

Service rate μ_s^n is the capacity of the secondary network divided by the number of admitted SUs at a particular time, which is a function of the SNRs/modes pair. It can be expressed as,

$$\mu_s^n = \frac{\sigma_n}{\sum_{\phi\in \text{ɕ}} V_n \pi(\phi)} \tag{25}$$

6.4. *CTMC Analysis for Readjustment Based Strategy.*

This is similar to the IBS scheme. The difference is that the CRBS adjusts between the minimum and maximum number of channel slots a SU can aggregate depending on the availability of resources and the arrival of a PU. The feasible state can be expressed as, $\text{ɕ} = \{(\omega, V_g, V_m, V_b) \mid \omega + \theta_n^{max} V_n < M * S\} \cup \{z(\phi) = M * S\}$

6.5. *Performance Measures for RBS*

In the RBS, the performance measures applied have similar procedures like the IBS. The State transitions are summarized in Table 3. The derivations are based on the premise of [6-7]. However, there are some variations due to the flexibility of the RBS scheme when PU arrives. This makes the performance measures different.

(a) *The Blocking Probability, $* P_b^n$*

The blocking $* P_b^n$ is expressed as

$$* P_b^n = \frac{Total\ SU\ blocking\ rate\ at\ a\ paticular\ channel\ state}{SU\ arrival\ rate\ at\ a\ particular\ channel\ state} \tag{26}$$

$$* P_b^g = \left[\sum_{\phi\in \text{ɕ}} \frac{\theta_g^{min} V_g}{z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi\in \text{ɕ}} \frac{\theta_g^{min} V_g}{z(\phi)} \pi(\phi)\right],\ \theta_{su} \le \sum_{i=1}^{V_g} \theta_{g_i}^{min},\ M * S - z(\phi) < \theta_g^{min} \tag{27}$$

where P_b^g is the blocking probability in good wireless link. Note that the symbol $*$(asterisk) is used to differentiate the RBS metrics from the IBS and is not a multiplication or convolution.

$$* P_b^m = \left[\sum_{\phi\in \text{ɕ}} \frac{\theta_m^{min} V_m}{z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi\in \text{ɕ}} \frac{\theta_m^{min} V_m}{z(\phi)} \pi(\phi)\right],\ \theta_{su} \le \sum_{i=1}^{V_m} \theta_{m_i}^{min},\ M * S - z(\phi) < \theta_m^{min} \tag{28}$$

where $* P_b^m$ is the blocking probability when the wireless link is in moderate wireless link.

$$* P_b^b = \left[\sum_{\phi\in \text{ɕ}} \frac{\theta_b^{min} V_b}{Z(\phi)} \pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\phi\in \text{ɕ}} \frac{\theta_b^{min} V_b}{Z(\phi)} \pi(\phi)\right],\ \theta_{su} \le \sum_{i=1}^{V_b} \theta_{b_i}^{min},\ M * S - Z(\phi) < \theta_b^{min} \tag{29}$$

where $* P_b^b$ is the blocking probability when the wireless link is in bad wireless link.

(b) *The forced termination probability, $* P_{ft}^n$*

With similar definition, it can be expressed as

$$* P_{ft}^g = \left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_g^{min} V_g}{Z(\phi) - \omega} \pi(\phi)\right] \Big/ (1 - P_b^g)\lambda_s = \frac{1}{(1 - P_b^g)\lambda_s}\left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_g^{min} V_g}{Z(\phi) - \omega} \pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min},\ M * S = Z(\phi) \tag{30}$$

where $* P_{ft}^g$ is the FT probability when the wireless link is in good wireless link

$$* P_{ft}^m = \left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_m^{min} V_m}{z(\phi) - \omega} \pi(\phi)\right] \Big/ (1 - P_b^m)\lambda_s = \frac{1}{(1 - P_b^m)\lambda_s}\left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_m^{min} V_m}{z(\phi) - \omega} \pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}^{min},\ M * S = z(\phi) \tag{31}$$

where $* P_{ft}^m$ is the FT probability when the wireless link is in moderate wireless link

$$* P_{ft}^b = \left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_b^{min} V_b}{z(\phi) - \omega} \pi(\phi)\right] \Big/ (1 - P_b^b)\lambda_s == \frac{1}{(1 - P_b^b)\lambda_s}\left[\lambda_p \sum_{\phi\in \text{ɕ}} \frac{\theta_b^{min} V_b}{z(\phi) - \omega} \pi(\phi)\right],\ \theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}^{min},\ M * S = z(\phi) \tag{32}$$

where $* P_{ft}^b$ is the FT probability when the wireless link is in bad wireless link (*c*) *Acceptance/Admission probability*, $* P_a^n$

As stated in the IBS scheme, the acceptance/admission probability is given as

$$* P_a^n = (1 - P_b^n) \tag{33}$$

For each wireless link condition, it can be expressed respectively as follows

$$* P_a^g = \left(1 - P_b^g\right) \tag{34}$$

where P_a^g is the acceptance/admission probability when the wireless link is in good condition.

$$* P_a^m = (1 - P_b^m) \tag{35}$$

where $* P_a^m$ is the acceptance/admission probability when the wireless link is in moderate condition.

$$* P_a^b = \left(1 - P_b^b\right) \tag{36}$$

where P_a^b is the acceptance/admission probability when the wireless link is in bad condition.

(*d*) *Capacity*, $* \sigma_n$

The capacity of the SU is the average service rate of the SUs i.e., the average number of SUs serviced completed per unit time [28]. It can be expressed as

$$* \sigma_n = \sum_{\phi \in \text{ɖ}} \sum_{i=1}^{V_n} * \mu_s^n \theta_{n_i}^{min} \pi(\phi) \tag{37}$$

(*e*) *Service rate*, $* \mu_s^n$

Service rate μ_s is the capacity of the secondary network divided by the number of admitted SUs at a particular time, which is a function of the SNRs/modes pair. It can be expressed as

$$* \mu_s^n = \frac{* \sigma_n}{\sum_{\phi \in \text{ɖ}} V_n \pi(\phi)} \tag{38}$$

Table 3 Transition state table for the RBS Strategies $(\omega, \theta_{su}, \theta_n^{min}, \theta_n^{max})$

No.	Present State	Next state	Possible State Events	Transition Rate
(1)	(ω, V_g, V_m, V_b)	$(\omega - 1, V_g, V_m, V_b)$	PU departs from the system	$\mu_p \omega$
(2)		$(V_g - 1, V_m + 1, V_b)$ (external)	SU in good state with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ departs from the system after service completion	$\theta_m^{min} \mu_s V_g$ $\theta_m^{max} \mu_s V_g$
(3)		$(V_g - 1, V_m + 1, V_b)$ (internal)	SU with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ transits from good to moderate state.	$\left[\frac{\theta_m^{min} V_m}{z(\phi)}\right] \lambda_s$ $\left[\frac{\theta_m^{max} V_m}{z(\phi)}\right] \lambda_s$
			SU in bad state with a minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_m^{min} \mu_s V_b]$
			SU in bad state depart from after service completion.	$[\theta_m^{max} \mu_s V_m]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_m^{min} V_m}{z(\phi) - \omega}\right] \lambda_p$
(4)		$(V_g + 1, V_m, V_b)$ (external)	SU arrives into the system in good state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_g} \theta_{g_i}^{min})$ of the channel slots required by the V_g. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \forall\ z(\phi) < M * S$	$\left[\frac{\theta_g^{min} V_g}{z(\phi)}\right] \lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \forall \{M * S - z(\phi)\} < \theta_g^{min}$	
(5)		$(V_g + 1, V_m - 1, V_b)$ (internal)	SU AR. The SU in bad state with the maximum number of channel slots (θ_n^{max}) donates to newly arrived service.	$\left[\frac{\theta_b^{max} V_b}{z(\phi)}\right] \lambda_s$
			No **FT** occurred in this event i.e. FT = 0	FT = 0
			SU with minimum/maximum number of channel slot $(\theta_n^{min}/\theta_n^{max})$ transits from moderate to good.	Same as in (3)
			SU in good state with minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_g^{min} \mu_s V_g]$
			SU in good state **departs** from system after service completion.	$[\theta_g^{max} \mu_s V_g]$
			SU in good state **FT** due to PU arrival.	$\left[\frac{\theta_g^{min} V_g}{z(\phi) - \omega}\right] \lambda_p$

Table 3 Transition state table for the RBS Strategies $(\omega, \theta_{su}, \theta_n^{min}, \theta_n^{max})$ (continued)

No.	Present State	Next state	Possible State Events	Transition Rate
(6)		$(V_g, V_m, V_b - 1)$ (external)	SU in bad state with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ departs from the system after service completion (releases the channel slot).	$[\theta_b^{min}\mu_s V_b]$ $[\theta_b^{max}\mu_s V_b]$
(7)		$(V_g, V_m + 1, V_b - 1)$ (internal)	SU with minimum/maximum number of channel slot $(\theta_n^{min}/\theta_n^{max})$ transits from bad to moderate state.	$\left[\frac{\theta_m^{min}V_m}{z(\phi)}\right]\lambda_s$ $\left[\frac{\theta_m^{max}V_m}{z(\phi)}\right]\lambda_s$
			The SU in moderate state with minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_m^{min}\mu_s V_b]$
			SU in moderate state **departs** from the system after service completion.	$[\theta_m^{max}\mu_s V_m]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_m^{min}V_m}{z(\phi) - \omega}\right]\lambda_p$
(8)		$(V_g, V_m, V_b + 1)$ (external)	SU arrives into the system in bad state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_b}\theta_b^{min})$ of the channel slots required by the V_b. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b}\theta_{b_i}^{min}$, $\forall\ z(\phi) < M * S$	$\left[\frac{\theta_b^{min}V_b}{z(\phi)}\right]$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_b}\theta_{b_i}^{min}$, $\forall\{M * S - z(\phi)\} < \theta_b^{min}$	
			SU AR. The SU in bad state with the maximum number of channel slots (θ_n^{max}) donates to the newly arrived service.	$\left[\frac{\theta_b^{max}V_b}{z(\phi)}\right]\lambda_s$
			No **FT** occurred in this event, i.e. FT = 0	FT = 0
(9)		$(V_g, V_m - 1, V_b + 1)$ (internal)	SU with minimum/maximum number of channel slot $(\theta_n^{min}/\theta_n^{max})$ transits from moderate to bad state.	$\left[\frac{\theta_b^{min}V_b}{z(\phi)}\right]\lambda_s$ $\left[\frac{\theta_b^{max}V_b}{z(\phi)}\right]\lambda_s$
			SU in bad state with minimum number of channel slot (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_b^{min}\mu_s V_b]$
			SU in bad state departs from the system after service completion.	$[\theta_b^{max}\mu_s V_b]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_b^{min}V_b}{z(\phi) - \omega}\right]\lambda_p$
(10)		$(V_g, V_m - 1, V_b)$ (external)	SU in moderate state with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ state departs from the system after service completion (releases the channel slots).	$[\theta_m^{min}\mu_s V_m]$ $[\theta_m^{max}\mu_s V_m]$
(11)		$(V_g, V_m + 1, V_b)$ (external)	The SU arrives into the system in moderate state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_m}\theta_m^{min})$ of the channel slots required by the V_b. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_m}\theta_{m_i}^{min}$, , $\forall\ z(\phi) < M * S$	$\left[\frac{\theta_m^{min}V_m}{z(\phi)}\right]\lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_m}\theta_{m_i}^{min}$, $\forall\{M * S - z(\phi)\} < \theta_m^{min}$	
			SU AR. The SU in moderate state with the maximum number of channel slots (θ_n^{max}) donates to newly arrived service.	$\left[\frac{\theta_m^{max}V_m}{z(\phi)}\right]\lambda_s$

7. Numerical Results and Discussions

In this section, the numerical results based on our analysis and simulation, are presented to evaluate the system performance. Unlike literature which assumed a homogeneous channel condition (SNR) for SUs. In this work, the varying nature of the wireless link is considered with AMC which makes it heterogeneous and more realistic. MATLAB tool was used to run the simulations for each of the strategies. Moreover, we adopted parameters of [6-7], [9], [20], and 100 realized are averaged to obtain the final result from 10^6 iterations. However, the scenarios and concept differ slightly. $\lambda_p = 0.5$, $\lambda_s = 1.5$, $\mu_p = 0.5$, $* \ \mu_{su} = \mu_{su} = 0.82$, $\omega \leq 6$, $* P_a^n = 0.5$, $* P_b^n \leq 0.25$, $P_b^n \leq 0.25$, $P_{ft}^{n,} \leq 0.15$, $* P_{ft}^{n,} \leq 0.15$, $V_g = 6$, $V_m = 3$, $V_b = 2$, SNR = 15 − 30dB, $\theta_n^{min} = 2$, $\theta_n^{max} = 6$, $\theta_n = 3$, $M \geq 6$. Fig. 6 shows SU blocking probability for the two strategies at different wireless link (channel conditions), since we considered the varying nature of a wireless link. For each strategy, different channel conditions have different blocking probabilities. However, comparing the strategies of the RBS with the IBS strategies, one can argue that there is a significant improvement of the RBS scheme over the IBS due to its flexibility. The RBS scheme outperformed the IBS scheme in terms of blocking probability. As the service rate μ_{su} of the SUs improves as a result of good wireless link, the blocking probabilities decreases since more SUs will be served. In all scenarios (good, moderate and bad wireless links) assumed, RBS strategy has a lower blocking probability as compared to IBS.

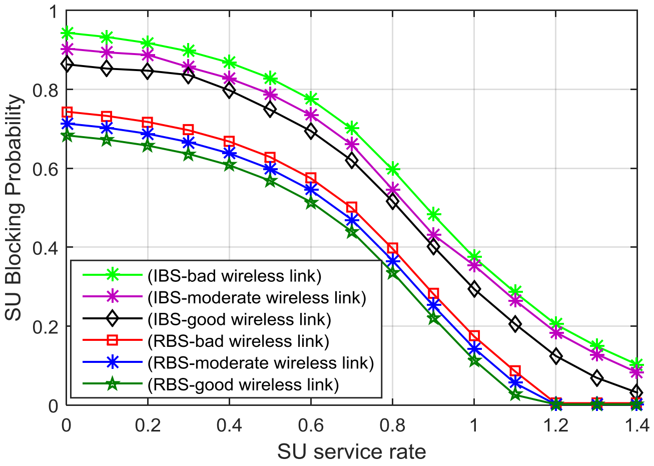

Fig. 6 SU blocking probability P_b^n vs μ_{su}

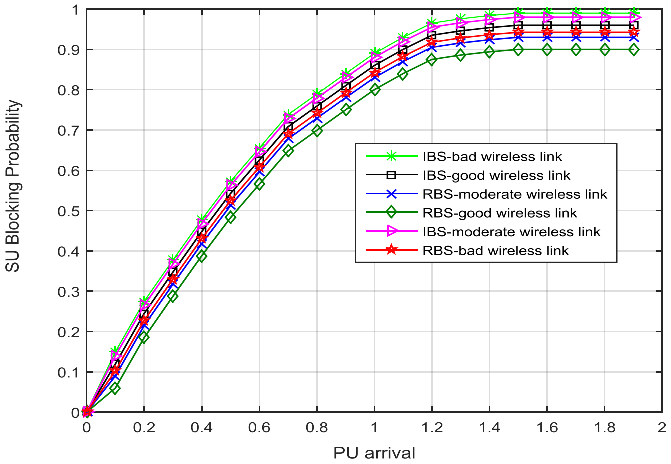

Fig. 7 SU blocking probability P_b^n vs PU arrival λ_p

In Fig. 7, the blocking probability rises sharply initially as λ_p arrive. This is due to traffic load to the PU network "batch arrival of PUs". This significantly affects the SU service since most channels would be occupied by the PUs, hence access would be denied. However, at each of the wireless link conditions, the RBS shows better improvement (lower blocking probability) than the IBS for the reason stated previously (adaptability). The relationship between Figs. 7 and 9 is that when the PU arrival rate is zero, the blocking probability would be zero. Hence, the access/admission would be at the highest point (approximately 1) since no PU is interrupting the SU ongoing services. However, as the PU gradually arrives, the blocking probability begins to grow and access start dropping. In Fig. 7, at PU arrival rate is 0 (PU absent) i.e. $P_b^n = 0$, access probability in Fig. 9 would be 1. Also, at PU arrival of 0.8, $P_b^n = 0.7$ while $P_a^n = 0.3$ with correlate and reaffirm the equation $P_a^n = 1 - P_b^n$.

In Fig. 8, PU arrival and departure have a significant effect on the behaviour of the SUs in terms of when to assemble channel slots and when to drop already assembled channels. When PUs arrive in batches or individually, an ongoing SU must be forced to terminate its transmission if idle channels does not exist elsewhere within the network. Likewise, when an SU arrives and enough channels exist, it is serviced and as such, the probabilities to force terminate these SU will drop. Moreover, in all of these scenarios, the RBS appears as a better strategy than the IBS in all wireless links due to its adaptability.

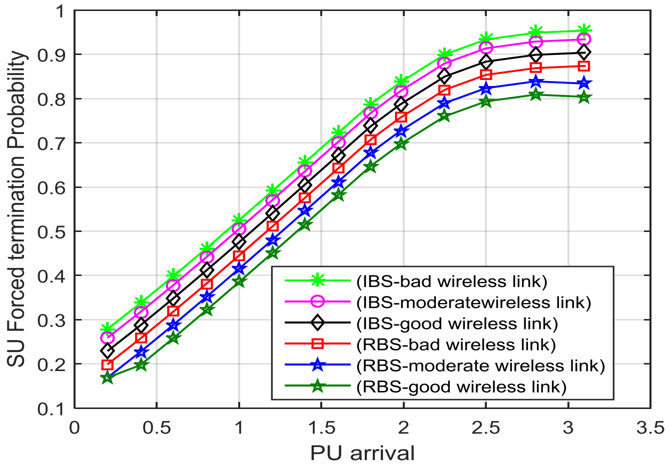

Fig. 8 SU forced termination probability P_{ft}^n vs λ_p

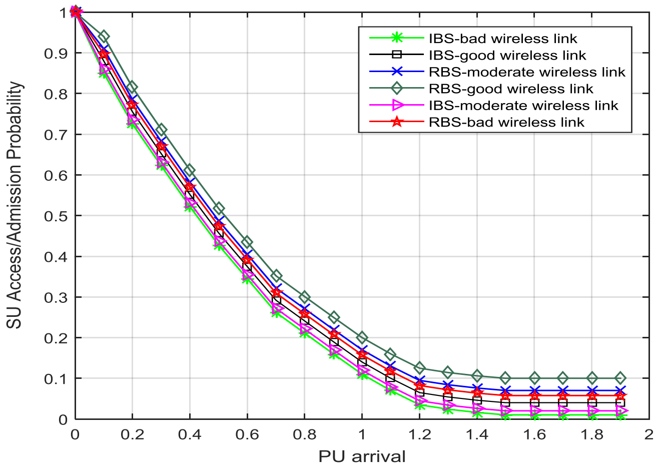

Fig. 9 SU Access/Admission Probability P_a^n vs λ_p

Fig. 9 demonstrates that in the event of batch arrivals of PUs, the SUs will experience impediments in gaining access/admission into the spectrum. This is because very few slots or no slot will be available for the SUs to use and as such, once the number of available slots is not enough based on the requirements, access will be blocked. Similarly, when PU departs more channels slots are made available for the SUs. However, the RBS still showed better performance as compared to the IBS in all the cases investigated due to adaptability with respect to PU arrival.

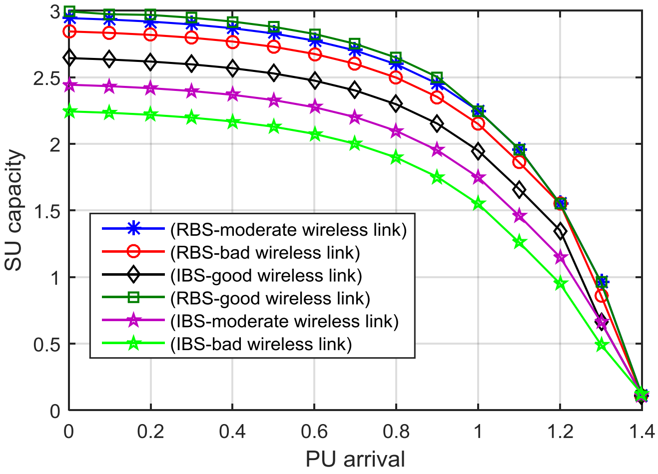

Fig. 10 SU Capacity σ_n vs PU arrival rate, λ_p

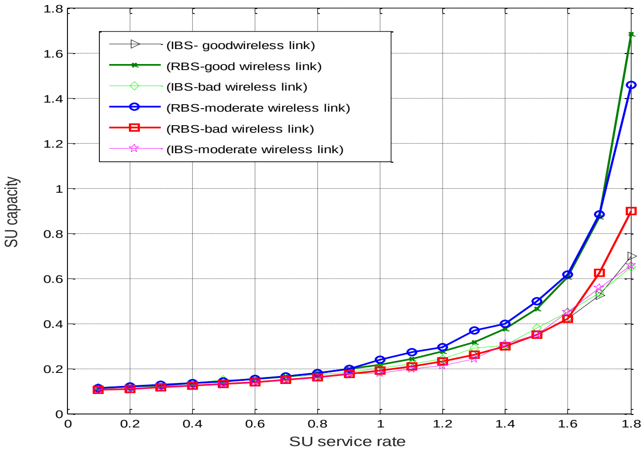

Fig. 11 SU Capacity σ_n vs SU service rate, μ_{su}

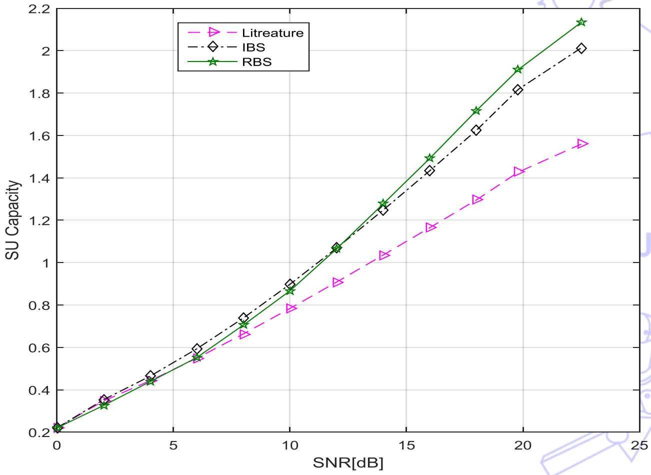

Fig. 12 SU Capacity σ_n vs SNR, γ

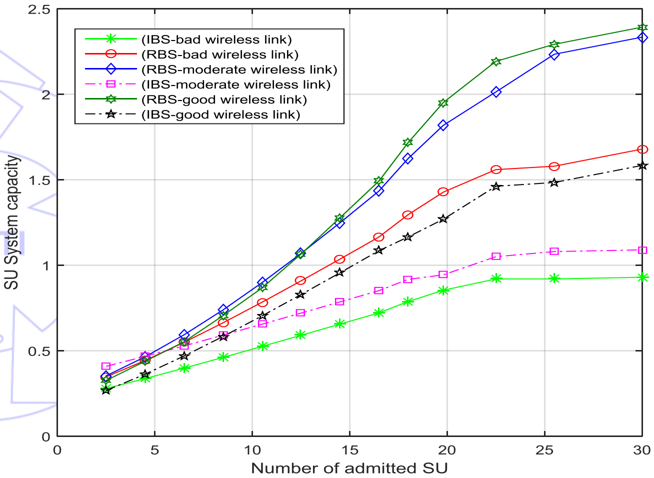

Fig. 13 SU System capacity σ_n vs Number of admitted SU, V

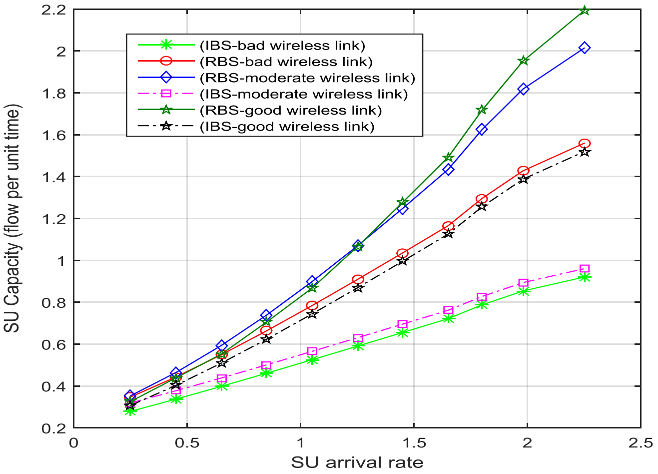

Fig. 14 SU Capacity (Flow per Unit time) σ_n vs SU arrival rate λ_S

In Fig. 10, our result clearly shows that the capacity (average service rate of the SUs, i.e. the average number of SU completions per time) was at the highest when the PUs were absent from the spectrum and as such, the SUs maximized the resources by assembling more channel-slots with high completion time irrespective of the wireless link condition and the strategies

(RBS or IBS) used by the SU. However, for each of the scenarios (good, moderate and bad) the RBS shows its robustness over the IBS when the PU begins to arrive into the spectrum. In an event of batch arrivals of PUs, the SUs will experience a decrease in capacity because very few channel-slots will be available for the SUs to use and as such, very little will be assembled by the SU. Similarly, capacity will improve as PU departs and more channels-slots are made available for SUs to use. Unlike in Fig. 10 where the capacity decreases as a result of the PU's arrival, in Fig. 11, it is the opposite. The capacity grows due to lesser traffic from the PU network activities hence; the SUs have the opportunity to complete their transmission without much interruption from the PUs. Both strategies experience significant improvement at different wireless link conditions. However, in the case of the RBS, due to its capability to aggregate more channel-slots as long as it has not reached the upper bound, it will continuously assemble channels. This makes the service completion rate higher than the IBS which assembles a fixed number of channel slots.

Most literatures [6-7,18], assumed that the SNR are homogeneous which is not always the case especially when investigating a dynamic wireless link. The result in Fig. 12 has shown that each wireless condition has different capacities. For example, the capacity of a SU when the SNR is in a good state is different from the capacity when the SNR is in a bad or moderate condition respectively. Also, the incorporation of AMC makes it obvious that the capacity of the RBS and IBS will improve as the SNR increases. The flexibility together with AMC accounts for the reason why the RBS and outperforms the IBS some point. Note the RBS is designed for non-real-time SUs and IBS for real-time SU. This implies that the IBS aggregates fixed number of channel slots just as real-time SU (e.g. calls or video conferencing) requires fixed number of resources. The RBS scheme aggregates a variable number of channel-slot just as non-real time SU (e.g. file downloading or browsing) do not have specific requirements. Therefore, it possible that at that particular SNR, enough channel slot exists in the system and because the IBS quickly aggregate its fixed number of channels, it slightly outperformed the RBSat some point. However, as the SNR becomes better the adaptive features of the RBS come into play and it begins to show its edge over the IBS.

In Fig. 13, when access/admission has been granted to the SU based on the criteria mentioned earlier, the SU then aggregates channel slots. The SU system capacity grows because it is the product of the number of admitted SUs and the number of channel slots assembled. As more SUs are admitted, more channel slots are allocated and the SU network capacity grows, showing that more PUs have departed from their channels. However, the RBS scheme improved the SU capacity compared to the IBS scheme for all channel conditions.

In Fig. 14, it is observed that SU arrival into the network has a direct link with the capacity, as shown in the results in Figs. 11, 12, and 13, respectively. What this implies is that the more SUs arrive, the more likely they are served. Recall that the arrival/admission of the SU is controlled by the CRBS which has an occupancy map of the entire PU network and behaviour. However, the RBS has a higher capacity compared to the IBS in the three channel conditions and can manage limited (insufficient) resources.

8. Conclusion

This paper proposed two CAS that considered; the dynamics of a wireless link, the impact of the SNR, the diversity of the SU traffic classes and AMC. An analytical framework to evaluate the performance of the strategies is developed. The developed strategies are compared in different channel conditions. The numerical results demonstrate that the RBS scheme outperformed the IBS scheme in different scenarios because it showed higher access/admission probability with lower blocking and forced termination probabilities. Similarly, this results shows that AMC is a robust technique when incorporated into CAS. However, assembling many channels slots irrespective of the channel condition might affect PER/BER, especially in a dynamic wireless link. Also, the security aspect of this work against cyber-attack (spy users/malicious users) will equally be studied and these will form the basis of future investigations.

References

[1] Y. Liang, K. Cheng, G. Y. Li, P. Mahonen, "Cognitive radio network and communication: an overview," IEEE Transactions on Vehicular Technology, vol. 60, no. 7, pp. 3386-3407, September, 2011.

[2] A. D. Domenico, E. C. Strinati, M.G. Di Beneditto, "Survey on MAC strategies for cognitive radio network," IEEE Communication Survey and Tutorials, vol. 14, no. 1, pp. 21-43, 2012.

[3] V. T. Nguyen, F. Villian, Y. L. Guillou, "Cognitive radio RF: overview and challengies," Hindawi Publishing Coporation, pp. 13, 2012.

[4] S. Hang, X. Zhang, "Cross-layer based opportunistic MAC protocol for QoS providing over cognitive radio wireless networks," IEEE Journal on Slected Area in Communication, vol. 26, no. 1, pp. 118-129, 2008.

[5] S. Haykin, "Cognitive radio: Brain-empowered wireless communications," IEEE Journal of Selected Areas in Communication, vol. 23, no. 2, pp. 201-220, February 2005.

[6] L. Jiao, F. Y. Li, and V. Pla, "Dynamic channel assembling strategies in cognitive radio networks with spectrum adaptation," in Proceedings IEEE GLOBECOM, Houston, TX, December 2011.

[7] L. Jiao, F. Y. Li, and V. Pla, "Modelling and performance analysis of channel assembling in multi-channel cognitive radio networks with spectrum adaptation," IEEE Transactions on Vehicular Technology, vol. 61, no. 6, pp. 2686-2697, July 2012.

[8] L. Jiao, E. Song, V. Pla, and Y. Li. Frank, "Capacity upper bound of channel assembling in cognitive radio networks with quasistationary primary user activities," IEEE Transactions on Vehicular Technology, vol. 62, no. 4, pp. 1849-1855, May 2013.

[9] L. Li, S. Zhang, K. Wang, and W. Zhou, "Combined channel assembling and fragmentation strategy in cognitive radio networks," arxiv preprint: http://arxiv.org/pdf/1203.4913v2.pdf, 13 June, 2012.

[10] E. Esenogho and T. Walingo, "Primary users ON/OFF behaviour models in cognitive radio networks," in International Conference on Wireless and Mobile Communication Systems (WMCS '14), Lisbon, Portugal, 2014.

[11] M. Wellens, J. Riihijarvi, P. Mahonen, "Modelling primary system activity in dynamic spectrum access network by assembling ON/OFF-process sensor," in 6th Annual IEEE Communication Society Conference on Mesh and Adhoc Communication and Network Conference SECON, Rome, June, 2009.

[12] H. Kim and K. G. Shin, "Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks," IEEE Transactions on Mobile Computing, vol. 7, no. 5, pp. 533-545, 2008.

[13] H. S. Wang, N. Moayeri, "Finite-state Markov channel—a useful model for radio communication channels," IEEE Transaction on Vehicular Technology, vol. 44, pp. 163-170, 1995.

[14] J. Razavilar, K. J. R. Liu, and S. I. Marcus, "Jointly optimized bit-rate/delay control policy for wireless packet networks with fading channels," IEEE Transactions on Communication, vol. 50, no. 3, pp. 484-494, March 2002.

[15] M.S. Alouini and A. J. Goldsmith, "Adaptive modulation over nakagami fading channels," Kluwer Journal Wireless Personal Communications, vols. 1-2, no. 13, pp. 119-143, May 2000..

[16] J. Lee and J. So, "Analysis of cognitive radio networks with channel assembling," in IEEE WCNC, Sydney, Australia, April 2010.

[17] T. N. Ngatched, S. Dong, and A. S. Alfa, "Analysis of cognitive radio networks with channel assembling, buffering, and imperfect sensing," in IEEE Wireless Communications and Networking Conference (WCNC), Shanghai, 2013.

[18] L. Jiao, F. Y. Li, and V. Pla, "Analysis on channel bonding/assembling for multi-channel cognitive radio networks," in IEEE European Wireless Conference (EW), Lucca, 2010.

[19] T. M. N. Ngatched, S. Dong, A. S. Alfa, and J. Cai, "Performance analysis of cognitive radio networks with channel assembling and imperfect sensing," Proc. IEEE International Conference on Communications (ICC), Ottawa, ON, June, 2012.

[20] L. Jiao, F. Li, and V. Pla, "Greedy versus dynamic channel assembling strategy in CRNs: markov models and performance evaluation," in IFIP Workshop on Performance Evaluation of Cognitive Radio Networks (PE-CRN), Valencia, Spain, 13 May 2011.

[21] E. Esenogho . T. Walingo, "Performance evaluation of channel assembling strategies with multi-class secondary users in cognitive radio networks," in Southern Africa Telecommunication, Networking and Application Conference (SATNAC), Cape Town, September, 2015.

[22] E. Esenogho and T. Walingo, "Evaluation of channel assembling strategies with single-class secondary users in cognitive radio networks," in IEEE Wireless Vitae, Hyderabad, India, 2015.

[23] I. A. M. Balapuwaduge, L. Jiao, V. Pla, F. Y. Li, “Channel assembling with priority-based queue in cognitive radio network: strategy and performance,” IEEE Transaction on wireless Communication, vol. 13, no. 2, pp. 630-644, February 2014.

[24] L. Li, S. Zhang, K. Wang and W. Zhou, “Queuing method in combined channel assembling and fragmentation strategy for dynamic spectrum access,” in 23rd IEEE Symposium on Personal, Indoor, and Mobile Radio Communication-(PIMRC), Sydney, NSW, September, 2012.

[25] C. C. Tseng, L. Wang, and C. H. Kuo, “Applications of differential CDMA schemes and control technology for distribution substations,” International Journal of Engineering and Technology Innovation, vol. 5, no. 4, pp. 242-254, 2015.

[26] X. Wang, Q. Liu, and G. B. Giannakis, “Analyzing and optimizing adaptive modulation coding jointly with ARQ for QoS-Guaranteed traffic,” IEEE Transactions On Vehicular Technology, vol. 56, no. 2, pp. 710-720, March 2007.

[27] Q. Liu, S.Zhou, and G. B. Giannakis, “Queuing with adaptive modulation and coding over wireless links: cross-layer analysis and design,” IEEE Transactions On Wireless Communications, vol. 4, no. 3, pp. 1142-1153, May 2005.

[28] Q. Liu, S. Zhou and G. B. Giannakis, “Cross-layer modeling of adaptive wireless links for QoS support in multimedia networks,” in First IEEE International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QSHINE’04), Dallas, TX, USA, 2004.

[29] R. Musumpuka, T. Walingo and F. Takawira, “Delay performance analysis of multi-rate M/Gc/1Queue with selective-repeat ARQ over Nakagami-m fading channel,” IEEE Letters for Wireless Communications, 2015.

[30] A. N. Mody, G. Chounard., “Enabling urural broadband wireless access using cognitive radio technology,” IEEE 802.22-10/007r03, June, 2010.

[31] C. Cordeir, K. Challapali, and D. Birru., “IEEE 802.22: An introduction to the first wireless standard based on cognitive radios,” Journal of Communications, vol. 1, no. 1, pp. 38-47, April 2006.

[32] X. R. Zhu, L. F. Shen, and T. S. P. Yum, “IEEE communication. letters,” Analysis of cognitive radio spectrum access with optimal channel reservation, vol. 11, no. 4, pp. 304-306, April 2007.