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Integrating Two Feedback Queuing Discipline into Cognitive Radio Channel Aggregation

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***Abstract*—Queuing regime is one outstanding approach in improving channel aggregation. If well designed and incorporated with carefully selected parameters, it enhances the smooth rollout of fifth/next generation wireless networks. While channel aggregation is the merging of scattered TV white space (spectrum holes) into one usable chunk for secondary users (SU). The queuing regime ensures that these unlicensed users (SUs) traffic/services are not interrupted permanently (blocked/dropped or forced to terminate) in the event of the licensed users (primary user) arrival. However, SUs are not identical in terms of traffic class and bandwidth consumption hence, they are classified as real time and non-real time SU respectively. Several of these strategies have been studied considering queuing regime with a single feedback queuing discipline. In furtherance to previous proposed work with single feedback queuing regime, this paper proposes, develops and compares channel aggregation policies with two feedback queuing regimes for the different classes of SUs. The investigation aims at identifying the impacts of the two-feedback queuing regime on the performance of the secondary network such that any SU that has not completed its ongoing service are queued in their respective buffers. The performance is evaluated through a simulation framework. The results validate that with a well-designed queuing regime, capacity, access and other indices are improved with significant decrease in blocking and forced termination probabilities respectively.**

***Keywords*—Cognitive radio, channel aggregation, primary and secondary users, queue discipline**

I. INTRODUCTION

THE MAIN aims and objectives of fifth generation (5G) networks is to deliver; high data rate, low latency, security reliability, self-awareness and cross-layer compatibility with other technologies or platforms. These cannot be achieved with the present day hard-wired radio system faced with challenge of congestion leading to spectrum crunch and scarcity. The proliferation of multimedia applications and services has expose the weakness of the current network architecture. As a panacea to this, cognitive radio was proposed in the 90's. So far, cognitive radio network is no longer a promising solution for supporting opportunistic spectrum access [1], [2] but a robust and proven network model that utilizes the 700-800 MHz TV-band as a complementary agent for decongesting the 1800/1900 MHz band which is faced with problem of shortage. This is founded on its ability to autonomously and dynamically adjust its operative transmission constraints, learn from previous and present terrestrial environs and make decisions based its knowledge [3], [4]. Furthermore, TV white space (TVWS/spectrum-holes) are created as a result of the irregular usage of primary channel by the primary user (PU), the licensed owner. Hence, this dispersed radio resources need harmonizing to satisfy the SU experience and so, channel aggregation policy is pertinent. Channel aggregation policy permits SU (unlicensed user) to merge numerous accessible PU spectrum holes to enhance SU throughput and as such minimize PU blocking, dropping and forced termination of SU traffic [5]. Cognitive radio functionalities are but not limited to; spectrum detection, spectrum organization, modification, allocation, and user circumventing, geolocation, etc. This investigation is focused in two folds; spectrum modification and allocation as a type of spectrum sharing. This involves the harmonization between SUs in accessing the PU channel in a centralized fashion (co-operatively) or in a distributive architecture (mesh). However, in this investigation, a centralised model is adopted due to so many advantages associated with it. Queuing as a user circumventing technique, enables SU to survive the unpredictable arrival and departure of PU irrespective of SU current events. While, channel aggregation cannot be discussed in seclusion from spectrum adaptation as a circumventing technique. Incorporating queuing regime into channel aggregation for SUs enhances traffic-flows such that transactions that would have been interrupted can possibly be queued in a buffer with a predetermine time and be served later. In literature, channel aggregation has been studied and implemented with and without queuing regime. While [6] proposed channel aggregation without queue, [7] and [8] considered channel aggregation integrating single feedback queuing regime which favours only one class of SU. This investigation, extend the body of knowledge in [8], [9] by proposing a channel aggregation policy with two-feedback queuing regime and its impact on the performance of the secondary network. Finally, the queuing model adopted in this investigation, is the general *M/G/1*. This implies that we are using a generalized one-sever (spectrum broker) called the cognitive radio base station (CRBS) which sense, coordinates and allocation TVWS for the SUs.

The rest of the paper is structured as follows: Section II summarized related works. The networks/system model of the proposed strategy is presented in Section III. Aggregation policies and performance measures are discussed in Section IV and V respectively. Numerical results with corresponding discussions are found in Section VI. Lastly, the paper is concluded in Section VII. Let it be noted that in this paper,

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regime and discipline are used interchangeable, same also goes for policy and strategy.

II. RELATED WORK

Studies on performance and analysis of channel aggregation have been reported in several literatures. In [10], the performance investigation of two channel aggregation policies with imperfect detection for wideband cognitive radio networks (CRN) were proposed. To be precise, the study considered false detection/alarm of PU presence as SU aggregate spectrum resources. In [11], queuing and channel fragmentation in were integrated in channel assembling strategy. This is a unique approach however; the scope of this investigation is not on fragmentation policy. [5] considered twofold spectrum adjustment strategies in a heterogeneous traffic scenario. The performance of these policies is evaluated and analysed on a proposed continuous time Markov model. [6] developed and investigated a mathematical equation for the hypothetical upper limit of the SU network with channel assembling. In [12], channel aggregation for real time traffic with channel adjustment were studied subject to channel accessibility and other SU events. In [13], the evaluation of channel assembling was investigated when spectrum adjustment was not applied. In the study, scenarios that were taken into account are without channel aggregation, with static and dynamic assembling, when SUs are granted admission into the network. Closely related works [9] proposed and compares through an investigative study, two channel aggregation policies. In the study, SUs services are instantly blocked if there are inadequate spectrum resources; while in the RBS, the spectrum is adjusted to accommodate new arrivals or other users for fairness purpose. However, a queueing regime is integrated into the IBS and RBS schemes to proposed $IBS+Q$ and $RBS+Q$ such that those services that would have been blocked or dropped are queued and served later using two feedback mechanisms for the two class of SUs. Thus, this to ensure fairness among the SUs since some can be greedy.

III. NETWORK/SYSTEM MODEL

The network/system model comprises of two autonomous spectrum brokers which are the primary user base station (PUBS) and cognitive radio base station (CRBS) which be called the secondary fusion center respectively. These spectrum brokers/managers have respective SUs, using the identical spectrum as shown in Fig. 1 and 3. The CRBS have two queuing regimes synchronised to compensate each other in the event of overflow due to batch arrival of the two-trafiic class of SUs as shown in Fig. 3. The queuing controller select the SUs with a last in last out (LILO) protocol. The PU requires a channel-slot whereas a secondary user combines more than one channel using the orthogonal access scheme, as shown in Fig. 3. The PU behaviour is characterized as a busy/idle but the secondary user optimistically and resourcefully aggregate several neighbouring channels. The essence of the feedback flow in Fig. 2, is to enable the SUs get the opportunity to access the spectrum after it service has been forcibly terminated. Force termination/dropping occurs in two folds; a) When the PU arrives and no other available channel for SU to switch to; b) within the queue when the SU over stayed the queue. However, the latter occurs at worse case scenarios.

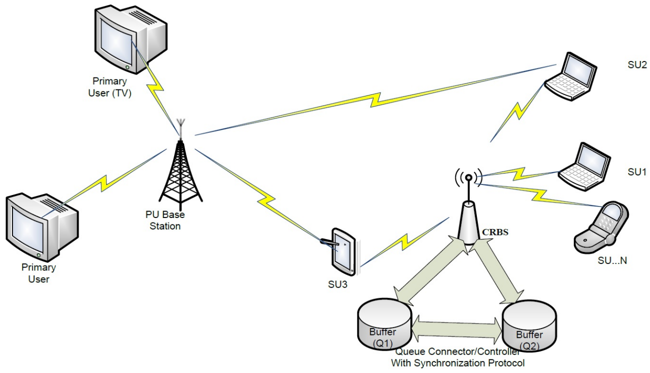

Fig. 1. Network/system Architecture

The channel utilization chart for a PU busy(ON)/idle(OFF) activities is illustrated in Fig. 3. The channel state utilization of PU is characterized as Markovian process as in [8], [9], with C_i, being the transition probability from ON state to OFF state and A_i being the transition likelihood from the idle state to the ON state for the l^{th} channel. For SUs, the CRBS detects diverse signal to noise ratio (SNR) since all SUs would not be the same. So, we assume the secondary user's SNR will either fall under good, moderate or bad SNR. The consequence of this flexibility is a heterogeneous structure with variable resource capacity such that SU traffic requires a precise communication rate or number of mini-slots for a certain channel link [8], [9].

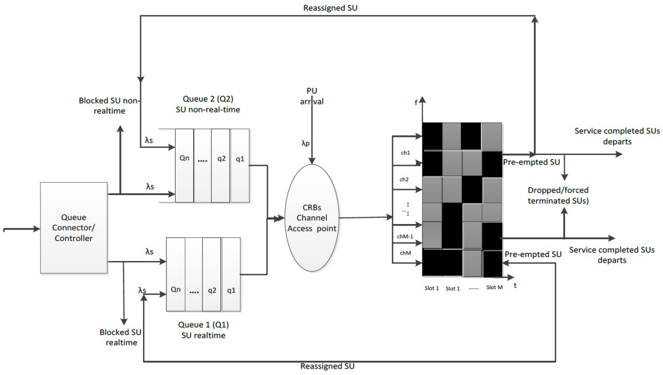

Fig. 2. Schematic of the proposed two feedback queuing regime deployed

A. Channel model

$Nakagami-m$ channel model is used to describe the wireless channel owing to its flexibility of covering bound of dwindling channels [14]. The channel quality is captured by the SNR while varying conditions are characterized by the Markov model whose analysis for slow fading channel conditions are well established in [14].

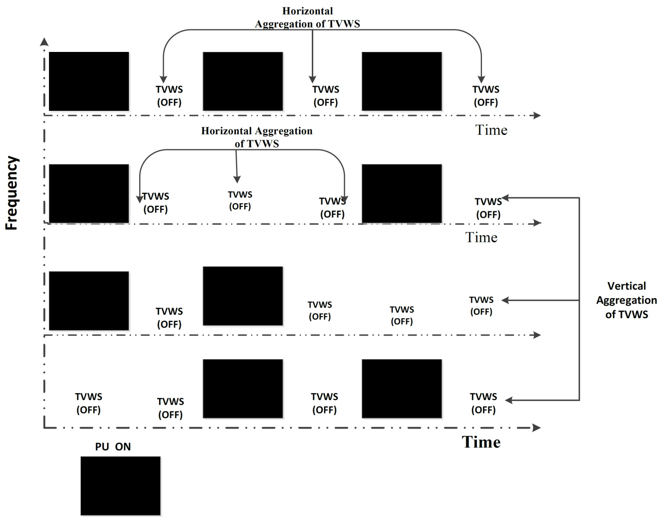

Fig. 3. SU utilizing TVWS orthogonally

B. SU frame structure

If the message length in bits be shown by π and r_p remain the number of bits carried per symbol for mode p, where the mode ranges $1 \leq n \leq P$, and N being the highest mode. The number of mini-slots X, in a frame for a coherent time interval, is a variable function of the dynamic SNR. X also corresponds to the number of slots in a frame for a coherent time interval. It can be expressed as:

$$S = \left(\frac{\pi}{r_p \varepsilon_s r_s}\right).r_p \tag{1}$$

Where ε_s is the channel constant, r_s denotes the symbol rate per seconds and r_p is the total capacity (cardinality) of the system given by $(W \times X)$ while the probability F_i of the PU channel being busy or idle is given as:

$$F_i = \begin{cases} 1 & i \in [1, W] \\ 0 & otherwise \end{cases}$$

F_i takes the value of 1 or 0. Note that $\vartheta_i = A_i/(A_i + C_i)$ is the channel utilization ratio. Therefore, the primary users channel slot capacity φ_P, is given as [9]:

$$\varphi_P = X.\sum_{i=1}^{W} \frac{A_i}{A_i + C_i} = X.\sum_{i=1}^{W}(\vartheta_i). \tag{2}$$

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

$$\theta_{su} = (W \times S) - \varphi_P \tag{3}$$

This implies that,

$$\theta_{su} + \varphi_P = W \times S \tag{4}$$

IV. AGGREGATION POLICIES

A. Instant blocking strategy with queue $(IBS + Q)$ $(\theta_{pu}, \theta_{su}, \theta_i, \theta_j, q)$

In $IBS + Q$ scheme, if there are no resources upon SU request the SU instead of instantly blocking it, the request is queue in q though can be blocked and dropped if and only if the queue is full and the SU over stayed on the queue. However, a SU that arrives first is given higher priority to the SU that arrives last and all the SUs are pre-empted by the arrival of a PU [9]. Assuming that, V denotes the number of SUs on the network and the resource demanded by SU_i, SU_j are θ_i and θ_j respectively. The aggregation protocol is shown in Table I.

TABLE I
ALGORITHM FOR $IBS + Q$ SCHEME

```
Algorithm for $IBS + Q$ scheme
// SU arrival
1: CRBS check wireless link state (SNR) and scan for free
spectrum / PU absence // cognitive radio base station checks for
free spectrum / PU absence.
2: CRBS check $\theta_{su}$; // cognitive radio base station checks
available recourse for SU
3: if $(\theta_{su} \geq \sum_{i=1}^{K} \theta_i)$ // test for $SU_i$ resources
4:   $SU_{i,j}\_admit = true$; // admit $SU_i$ and assemble
5: else
6: $SU_i\_admit = false$ $(block)$ // queue full, block new $SU_i$ due
to insufficient resources
7: else
8: if $(\delta_{SUi,j} < \delta_{max})$ // comparing delay time for $SU_i$
9: $SU_{i,j}\_drop\_queue = false$ // continue to wait in the queue
10: else
11: if $(\delta_{SUi,j} > \delta_{max})$ // comparing delay time for SUs
12:   $SU_{i,j}\_drop\_queue = true$ (forced terminate); // time-out in the queue
13: end if
// PU arrival
14: Go to step 1
15: if $(\theta_{su} < \sum_{i=1}^{K} \theta_i)$ // PU arrival pick some SU resources
16: Go to Do procedure above // call subroutine for SU
17: else
18: $SU_{i,j}\_drop\_queue = true$ // force terminate of ongoing SUs
19: end if // terminate if no event
// PU departure
20: Go to step 12:
21: if ($PU_i$ mini-slots = idle) // free mini-slots exist
21: $SU_{i,j}\_admit\_into\_queue = true$ // admit SUs and assemble
22: end
23: Go to start
```

B. Readjustment based strategy $(RBS + Q)$ $(\theta_{pu}, \theta_{su}, \theta_{i,j}^{min}, \theta_{i,j}^{max}, q)$

In this scheme, both SU_i and SU_j requires a minimum and maximum of $\theta_{i,j}^{max}$ and $\theta_{i,j}^{min}$ number of channels to commence or stop assembling respectively. If a SU_i requires services, the aggregation procedure checks for resource availability similar to the $IBS + Q$ scheme. If the resources are available and sufficient, SU_i is admitted, otherwise, readjustment algorithm is executed to reduce blocking and dropping. Every other procedure remains the same. The aggregation protocol is shown in Table II.

The computational burden of the two schemes are not similar for the following reasons: In $IBS + Q$ scheme, if there are no channels/resources upon SU arrival, instead of immediately blocking its request/services, it is queued in a buffer. While for the $RBS + Q$ scheme, there will be channel adjustment among SUs which have accumulated more channels to ensure that real time SUs are not dropped.

When this condition cannot be fulfilled, it will then invoke the queuing protocol else, it is then dropped/blocked. On the other hand, $IBS + Q$ are deployed for non-real time SUs (file downloading, internet surfing, applications etc.) while $RBS + Q$ are for real time SUs (voice calls, video calls and conferencing). However, in a nutshell, more computational power will be required for the RBS due to complex/lengthy algorithm. Hence, there is a trade-off between computational power and resource maximization. In this investigation, resource maximization is chosen over computational power.

Moreover, in this policy, the conditions that can possibly cause grant access or cause blocking, force termination of SU traffics are as follow:

- The available channel resources (channel slots) are less than the total of SU required resources.
- The spectrum adaptation has been implemented and yet there are no available or sufficient numbers of channel slots to make-up for the reduction because of PU arrivals.
- The new SU arrives, and both queues are full.
- The waiting time pre-determined by the CRBS exceeds the time spent by a SU in queues.
- The queue/buffer when empty, can grant access to SU traffic.
- Enough TVWS exist can equally grant admission.

Hence, to admit a SU, the available resources (channel slot) must be equivalent to or more than the SU requirement, irrespective of the traffic classes and wireless link condition or the buffer is totally empty or partially filled.

TABLE II
ALGORITHM FOR $RBS + Q$ SCHEME

```
Algorithm for $RBS + Q$ scheme
// SU arrival
1: CRBS check wireless link state (SNR) and scan for free spectrum holes // cognitive radio base station checks for spectrum holes
2: CRBS check $\theta_{su}$; //cognitive radio base station checks available resource for SU
3: if $(\theta_{su} \geq \sum_{i=1}^{K} \theta_{n_i}^{min})$ // test for $SU_a$ resources
4:   $SU_{i,j}$_admit_into_queue $= true$; // admit $SU_b$ and aggregate
5: else
6:   Do $(\theta_n^{max} - 1), ++SUs$; // $SU_b$ with highest number of channel, donate to new $SU_b$ and iterate over other higher $SU_b$ user resources
7: Go to next step // commences queue procedure
8: if $(q_2 < q_{2max})$ // queue not full/empty
9:   $SU_{i,j}$_admit_into_queue $= true$ // queue not full, allow new SUs
10: else
11:   $SU_{i,j}$_admit_into_queue $= false$; // queue-full, block new $SU_b$ no free / insufficient slot
12: else
13: if $(\delta_{SUi,j} < \delta_{max})$ // over delay in the buffer
14:   $SU_{i,j}$_drop_queue $= false$ // $SU_b$ still waiting in the queue
15: else
16: if $(\delta_{SUi,j} > \delta_{max})$ // over delay in the queue
17:   $SU_{i,j}$_drop_queue $= true$ // SUs timeout in the queue
// PU arrival
18: Go to step 1
19: if $(\theta_{su} < \sum_{i=1}^{K} \theta_{n_i}^{min})$ // PU arrival pick some resources
20: Go to Do procedure above // call subroutine for SU with maximum channel adjust downward
21:   $SU_{i,j}$_drop_queue $= true$ // force terminate of ongoing SUs
// PU departure
22: Go to step 1
23: if $PU_i$ channel slots are idle // free channel slots exist
23:   $SU_{i,j}$_drop_queue $= true$ // admit SUs and assemble
24:   Do $(\theta_n^{min} + 1)$ // call subroutine for SU with minimum channel to adjust upward since PU has departed
25: end
26: Go to start
```

V. SYSTEM MODEL PERFORMANCE ANALYSIS

The performance analysis is based on the premise of [9]. Arrival rates of the PU and SU follows a *Poisson distribution* while the service time is exponentially distributed with the service and arrival rates well-defined as μ_p, μ_s, λ_p, and λ_s, for the PU and SU respectively. The total rate for a SU is taken as the multiplication of the SU channel service rate and the number of aggregated channels $\theta_i \mu_{si}$ or $\theta_j \mu_{sj}$.

1) *Blocking probability* $(P_{bs_{i,j}})$ of SU is the fraction of total SU blocked to the total SU arrived. If total SU blocked and arrived are $\Omega_{Ts_{i,j}}$ and $\lambda_{Ts_{i,j}}$ respectively, then , It is expressed as:

$$P_{bs_{i,j}} = \frac{\textit{Sum of secondary user blocking rate}}{\textit{Sum secondaty user arrival rate}} = \frac{\Omega_{Ts_{i,j}}}{\lambda_{Ts_{i,j}}} \tag{5}$$

2) *The forced termination probability* $(P_{fs_{i,j}})$, ratio of total SU dropped to the total admitted SU connection. Similarly, if the total SU forced terminated and admitted are $\eta_{Ts_{i,j}}$ and $\zeta_{Ts_{i,j}}$ respectively.it is expressed as:

$$P_{fs_{i,j}} = \frac{\textit{Total secondary user forced terminated}}{\textit{Total admitted SU connections}} = \frac{\eta_{Ts_{i,j}}}{\zeta_{Ts_{i,j}}} \tag{6}$$

3) *Access Probability* $(P_{as_{i,j}})$, is defined as the likelihood that enough resources exist for the SU when it arrives after meeting the necessary conditions in the algorithms. It can be given as:

$$P_{as_{i,j}} = 1 - P_{bs_{i,j}} \tag{7}$$

4) *Queue size* δ_l: In this investigation, the size/length of the queue depends of the arrival rates of the SUs and service completion rates. q_1 and q_2 are the queue sizes for buffer 1 and 2 respectively.

5) *Capacity* $\rho_{s_{i,j}}$: the capacity of the SU traffic is the mean number of SU service completion per unit time. Thus, $\rho_{s_{i,j}}$ of accepted SU at a time is dependent on the SNRs per modes pair. It is expressed as:

$$\rho_{s_{i,j}} = \frac{\textit{mean number of SUs service completion}}{\textit{Time (seconds)}} \tag{8}$$

6) *Average total delay of the schemes* $\Phi_{(i,j)}$: The average total delay of the SUs irrespective of the scheme, is the sum of the average broadcast time $\Phi_{(i,j)}^t$ and the mean waiting time $\Phi_{(i,j)}^q$ of SUs services in the buffer respectively. Let $\gamma_{(i,j)}^s$ be the mean number of current SUs services while $\Phi_{(i,j)}^t$ denotes the mean transmission

time of SUs services. $\Phi^q_{(i,j)}$ represents the mean waiting time of SUs services in the queues and $\Phi_{(i,j)}$ are the mean total delay of SUs respectively.

From Little's theorem [16], [17], the mean total delay of the SUs services is given as

$$\begin{aligned}\Phi_{(i,j)} &= \Phi^q_{(i,j)} + \Phi^t_{(i,j)} \\ &= \frac{\delta_{l(i,j)}}{\lambda_s + \lambda_{sm}} + \frac{\gamma^q_{l(i,j)}}{\lambda_s + \lambda_{sm}}\end{aligned} \tag{9}$$

Where λ_s and λ_{sm} are the mean arrival rate of the admitted $SU_{(i,j)}$ and average feedback arrival rate of $SU_{(i,j)}$ into q_1 and q_2 respectively. Hence,

$$\begin{aligned}\Phi_{(i,j)} = \Phi^q_{(i,j)} + \Phi^t_{(i,j)} &= \frac{\delta_{l(j)} + \gamma^s_j}{\lambda_{s(i,j)} + \lambda_{sm}} \\ &= \frac{\delta_{l(j)} + \gamma^s_{i,j}}{\lambda_{s(i,j)} + \lambda_{sm}}\end{aligned} \tag{10}$$

If λ_{sm} is negligible assumed

$$\Phi_{(i,j)} = \frac{\delta_{l(i,j)} + \gamma^s_{(i,j)}}{\gamma_{s(i,j)}} \tag{11}$$

Let $\omega_{(i,j)}$ represent the number of times an ongoing SUs is fed back into q_1 and q_2 respectively after interruption. Therefore,

$$\begin{aligned}\Phi_{(i,j)} &= \left(\frac{\delta_{l(i,j)} + \gamma^s_{(i,j)}}{\gamma_{s(i,j)}}\right) \cdot \omega_{(i,j)} \\ &= (\Phi^q_{(i,j)} + \Phi^t_{(i,j)}) \cdot \omega_{(i,j)}\end{aligned} \tag{12}$$

VI. NUMERICAL RESULTS AND DISCUSSIONS

This section presents the performance of the dual channel aggregation policies with queueing discipline. The numerical results are based on the system simulation. Parameters are set as in [9]. In Fig. 4 the increase in P_b is a function of PU arrival λ_p. This growth is due to batch arrival of PU into their spectrum. This however, impact the SU' service since most channel slots are occupied by the PU and as such, access will be deprived to SUs. Therefore, the blocking probability increases. However, in this case, the $RBS + Q$ results outperformed the $IBS + Q$ due to its flexibility.

Fig. 5 shows the effect of incorporating buffer regime into channel aggregation. This gives the SUs the opportunity (avenue to wait) to access the spectrum whenever the PU interrupts their services or if the SU experiences insufficient or no resources. As the queue length increases, the likelihood of SU accessing the scarce resources grows and at a point, begins to saturate due to limited buffer capacity. Fig. 6 explains the impact of the queuing regime on the forced termination probability as soon as the PU interrupts SU traffic flow. As the queue size rises (more SUs being buffered) the forced termination probability drops significantly since a “second chance” will be given to SUs. However, when a SU exceeds its waiting time in the queue irrespective of the class, it will be dropped. This is to avoid starvation of other SUs waiting in the queue. Fig. 6 explains the impact of the queuing regime on the forced termination probability as soon as the PU interrupts SU traffic flow. As the queue size rises (more SUs being buffered) the forced termination probability drops significantly since a ”second chance” will be given to SUs. However, when a SU exceeds its waiting time in the queue irrespective of the class, it will be dropped. This is to avoid starvation of other SUs waiting in the queue.

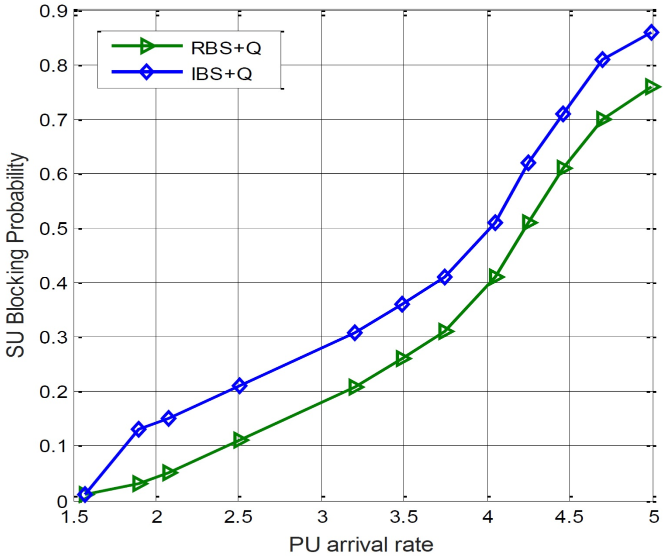

Fig. 4. P_b vs. λ_p

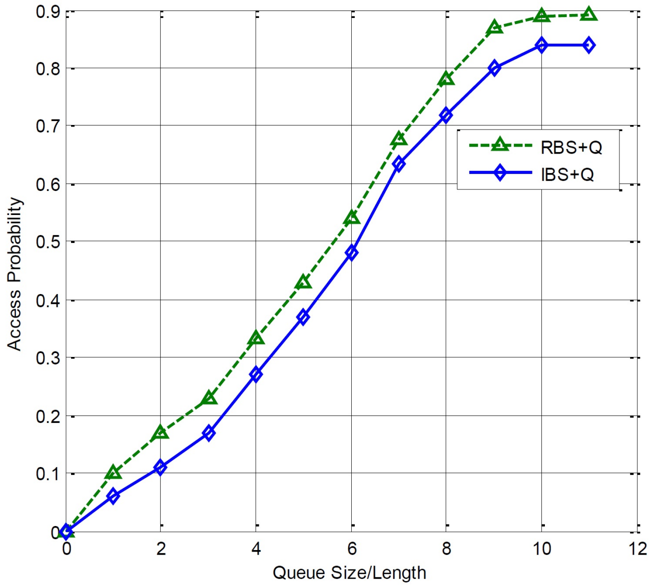

Fig. 5. P_a vs. δ_l

In Fig. 7, both policies showed improved SUs capacity as the queue size increases. This implies that more SUs have been given the opportunity to transmit their packets that would have been dropped when the PU arrives while SUs are still using the spectrum. However, the flexibility of the $RBS + Q$ is still an advantage over the $IBS + Q$.

The consequence of integrating a queuing system is the extra delays which the SUs experience on the buffer, as it waits for service. Fig. 8 shows the outcome of queue size on the total delay, precisely both SUs. The interrupted $SU_{i,j}$ is rerouted

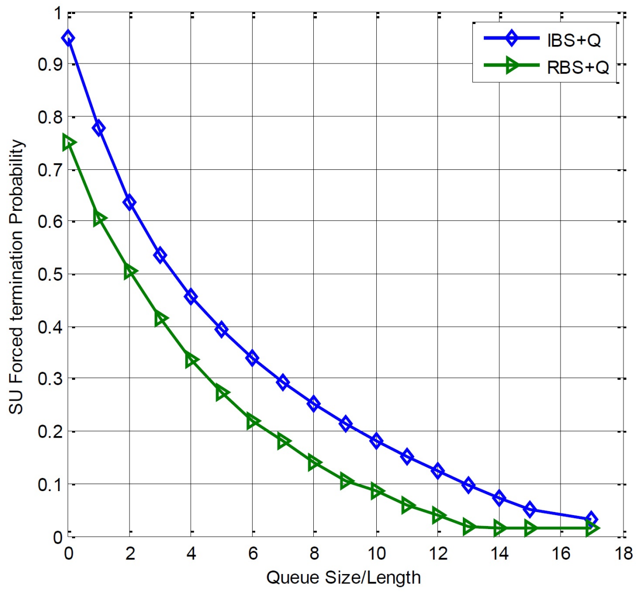

Fig. 6. P_f vs. Queue size

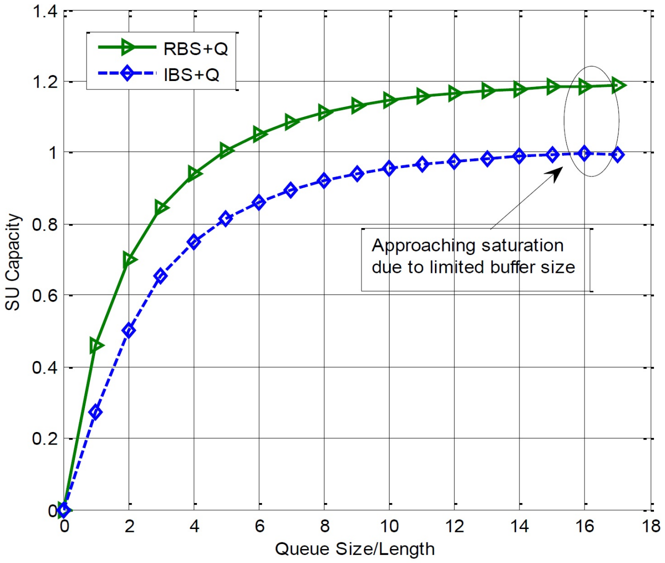

Fig. 7. SU Capacity vs. Queue size

back into the queue to reduce instant forced termination while the new arriving SU is buffered to avoid instant obstruction thus, both arrivals increase the queue length. These joint arrival of $SU_{i,j}$ sums up to $\lambda_{s(i,j)} + \lambda_{sm}$ for the new and interrupted respectively. Therefore, the queue length of the SUs will be longer due to more arrivals. In Fig. 9, as the SUs continue to queue in the buffer, it gets the privilege to re-access the spectrum. This in turn reduce the rate at which the SUs service are dropped, blocked or forcibly terminated. However, the RBS policy is more robust than the IBS due to it capability to adjust and adapted PU ON/OFF arrival and departure.

VII. CONCLUSION

By comparing the two strategies $RBS + Q$ and $IBS + Q$, there is a substantial superiority of the $RBS + Q$ scheme over

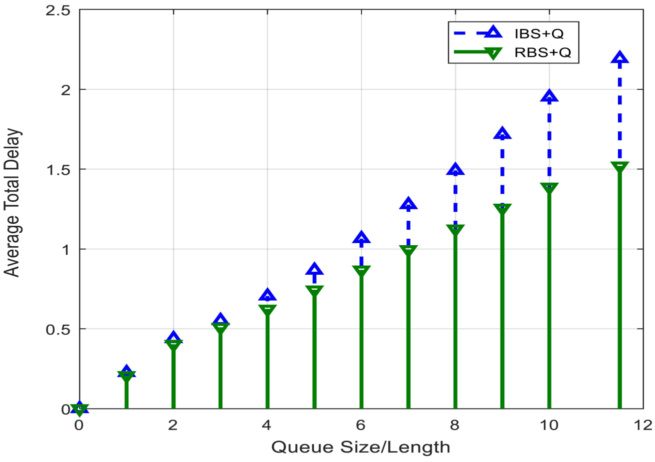

Fig. 8. $\Phi_{(i,j)} vs. \delta_l$

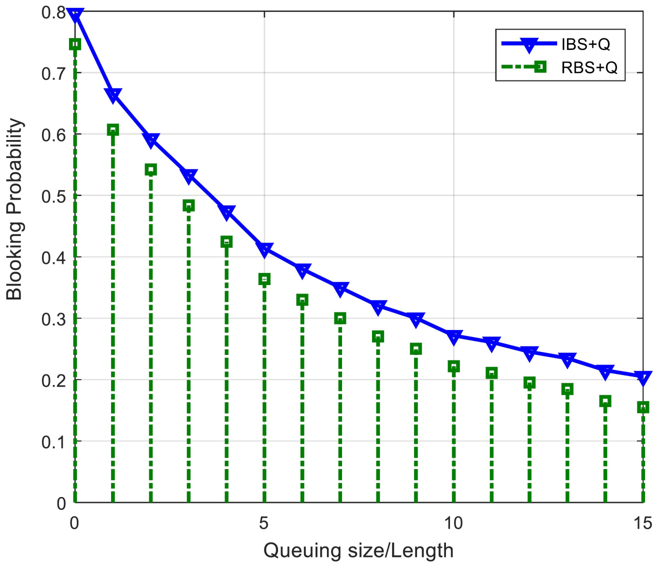

Fig. 9. P_b vs. δ_l

the $IBS + Q$ due to its adaptability. Precisely, the $RBS + Q$ scheme outperformed the $IBS + Q$ scheme in terms of SU blocking, forced termination, and access probabilities respectively. It demonstrates that AMC with queueing technique is a robust method in improving channel aggregation schemes. Our future work will focus on simulating more than two traffic class and a detailed performance analysis using either any of: continuous time Markov chain (CTMC) or game theory approach.

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