Channel Quality Feedback-Based Access Scheme for Cognitive Radio Systems

Sara A. Attalla[‡], Karim G. Seddik[‡], Amr A. El-Sherif[+†], and Sherif I. Rabia[*]

[‡]Electronics and Communications Engineering Department, American University in Cairo, AUC Avenue, New Cairo 11835, Egypt.
[+]Wireless Intelligent Networks Center (WINC), Nile University, Giza 12588, Egypt.
[†]Department of Electrical Engineering, Alexandria University, Alexandria 21544, Egypt.
[*]Department of Engineering Mathematics and Physics, Alexandria University, Alexandria 21544, Egypt.
Email: saraattlla@aucegypt.edu, kseddik@aucegypt.edu, aelsherif@nu.edu.eg, sherif.rabia@alexu.edu.eg

***Abstract*—In this paper, the performance of a cognitive radio system is studied in which the secondary user can overhear the primary user's channel quality indicator (CQI) feedback information, sense the primary user's existence, and use this information to select the probability with which it will access the channel in the next time slot. This access probability is selected such that the secondary user's throughput is maximized while the stability of the primary user data queue is guaranteed. We model the system as a multi-dimensional Markov chain to find a closed form expression for the secondary user throughput, the primary user delay, and to formulate the access probability selection problem as a constrained optimization problem. Results reveal that the proposed scheme outperforms the schemes where no feedback information is exploited in terms of secondary user's throughput. This is due to the fact that the secondary user's awareness of the CQI feedback information allows it to access the channel more aggressively when it knows that the primary user is not accessing the channel due to its bad channel conditions.**

I. Introduction

Cognitive radio is a communication technology that tries to solve the spectrum scarcity problem and the inefficient use of the radio spectrum [1].

Typical cognitive radio models are based on cognitive transmitter sensing of the primary activity and accessing the channel on the basis of the sensing outcome. This model is problematic because sensing does not inform the cognitive terminal about its impact on the primary receiver. To alleviate this disadvantage, the idea of enabling the SU to leverage the feedback sent from the primary receiver to the primary transmitter, and to optimize its transmission strategy based on its effect on the primary receiver has appeared. The authors in [2] have proposed a system where the SU observes the automatic repeat request (ARQ) sent from the primary receiver. This ARQ feedback messages reflect the PU's achieved packet rate. The SU's objective is to maximize its throughput under the constraint of guaranteeing a certain packet rate for the PU. In [3], the authors designed an access scheme for SU based on the PU ACK/NACK feedback, which enhances the system performance in terms of SU's throughput and PU's packet delay. In [4], the authors presented a system in which the SU takes access decisions based on the ACK/NACK feedback from the PU receiver as well as soft spectrum sensing information of the PU activity. In [5], based on the ACK/NACK received, the authors devised optimal transmission strategies for the cognitive radio so as to maximize a weighted sum of primary and secondary throughput, which is determined by the degree of protection afforded to the primary link.

A different type of feedback information, namely, the channel quality indicator (CQI) feedback, informs the PU transmitter about the state of the channel. Using this feedback information, the PU adjusts its transmission parameters to achieve the maximum transmission rate or the minimum packet loss rate. In [6], the authors developed a spectrum sharing scheme for the SU based on primary CQI feedback. They also derived the optimal transmit power and transmission rate for the SU when no or perfect primary CQI is available at the secondary transmitter by maximizing its average throughput while satisfying the rate loss constraint of the primary system.

In our work, we study the effect of exploiting the CQI feedback by the SU from the point of view of queuing theory, which enables us to derive a closed form expression for the SU throughput as well as the PU delay. The CQI is used in many standards for wireless communication such as Long-Term Evolution (LTE). In LTE, there are 15 different CQI values [7]. Here we assume that the CQI feedback has only two states, informing the PU transmitter whether the channel is good and a successful transmission is expected, or bad and any transmission is most likely to fail. In the case of a bad CQI feedback, the PU refrains from transmitting any packets since transmissions are most likely to fail. In this paper, we compare our proposed system with two baseline systems. It is assumed in all systems that the SU accesses the channel based on the hard spectrum sensing decisions [8]. The first baseline system has no PU CQI feedback. The second baseline system has a PU CQI feedback but the SU cannot access this feedback information. In the proposed scheme, by overhearing the CQI feedback, the SU can exploit the time slots where the PU channel is bad to access the channel with a high access probability knowing that the PU is idle for sure. In all systems, the SU access probability is determined by solving an optimization problem that maximizes the SU's throughput subject to a constraint on the PU's queue stability. We study and compare the performance of the three systems by finding closed form expressions of the secondary throughput and the PU delay for each system.

II. System Model

We consider a cognitive system consisting of one PU and one SU. The system is time-slotted, and it is assumed that the duration of one time slot equals the time of one packet transmission. It is assumed that the packets arrive at the start of the time slot, which means that a packet can be served in the same time slot it arrives at. The PU accesses the channel at the start of each time slot whenever there is a packet to transmit and the channel is in the good state. The PU and SU have an infinite buffer for storing fixed length packets. The arrival process at the PU queue is a Bernoulli process with mean $0 < \lambda_p < 1$. The SU is assumed to always have packets in its queue.

The channel between the PU transmitter and receiver is modelled as a two-state Markov chain as shown in Fig. 1. The probabilities of the channel staying in the good state and in the bad state are p_g and p_B, respectively. The steady state probabilities of the channel being in the good state and in the bad state are ζ_g and ζ_B, respectively and can be calculated using the following equations:

$$\zeta_g = \frac{1-p_B}{2-p_B-p_g}, \text{ and } \zeta_B = \frac{1-p_g}{2-p_B-p_g}. \quad (1)$$

It is assumed that the channel state does not change during one time slot. Furthermore, collision channel model is assumed, i.e., if both the PU and SU transmit in the same time slot, then a collision occurs and both packets are lost.

In our model, the SU employs hard decision sensing scheme to sense the PU's presence. The SU makes a binary decision on whether the PU is present or not by comparing the sensed energy with a threshold. The SU accesses the channel with access probability a_s when the detected energy is less than the threshold as the SU does not detect the PU's existence. These access probabilities are selected such that the SU throughput is maximized and the stability of the PU queue is guaranteed. Stability can be loosely defined as having a certain quantity of interest kept bounded, in our case, the queue size. For more information about stability, see [9] and [10]. If the arrival and service processes of a queuing system are strictly stationary, one can apply Loynes' theorem to check for stability [11]. This theorem states that if the average arrival rate is less than the average service rate of a queuing system, whose arrival and service processes are strictly stationary, then the queue is stable, otherwise it is unstable.

In the following subsections, different SU access schemes are presented.

A. The Baseline Systems

1) The No CQI Feedback- based Access System (Baseline System 1 NO FB):: In this system, the PU has no CQI feedback information. Therefore, the PU transmits its packets regardless of the state of the channel. The SU accesses the channel with an access probability a_s in every time slot based on the hard decision sensing scheme.

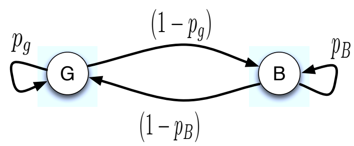

Fig. 1: The channel model

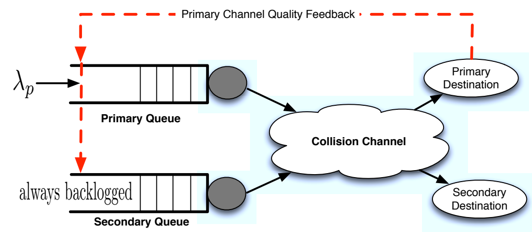

Fig. 2: The system model

2) The PU CQI Feedback- based Access System (Baseline System 2 NO FB SU:: The PU has a CQI feedback of the channel state in the next time slot, which is an indicator of how good/bad the channel between the PU transmitter and receiver is. If a good CQI feedback is observed, the PU transmits whenever it has packets in its queue. Observing a bad PU CQI feedback, the PU backs-off since it knows that the packet will not be received correctly. However, the SU does not monitor the PU CQI feedback. The SU accesses the channel with an access probability a_s in every time slot based on the hard decision sensing scheme.

B. Proposed CQI Feedback-based Access System

The proposed system model is shown in Fig. 2, in which the PU has a CQI feedback of the channel state in the next time slot, and the SU listens to this CQI feedback. The SU accesses the channel depending on the hard decision sensing scheme and the primary CQI feedback. If a good CQI feedback is observed and the SU does not detect the PU's existence, the SU accesses the channel with access probability a_s. If a bad CQI feedback is observed, the SU exploits the knowledge that the PU will back-off during the next time slot to transmit with probability 1.

III. Performance Analysis

In this section, we present the analysis of the PU's queue for the following systems:

A. The Baseline Systems and The Proposed System

The PU's queue in the two baseline systems and the proposed system is modelled using the same two-dimensional Markov model shown in Fig. 3; the same Markov chain is used for the three systems as the PU queue dynamics in the bad channel states will not be affected by the SU access decisions (as the PU will always fail in the case of a bad channel). Moreover, in the PU good channel states, the SU accesses the channel with an access probability of a_s if the SU does not detect the PU's existence (where the access probabilities that will maximize the secondary throughput in each of the three systems will be different). Finally, each system will have a

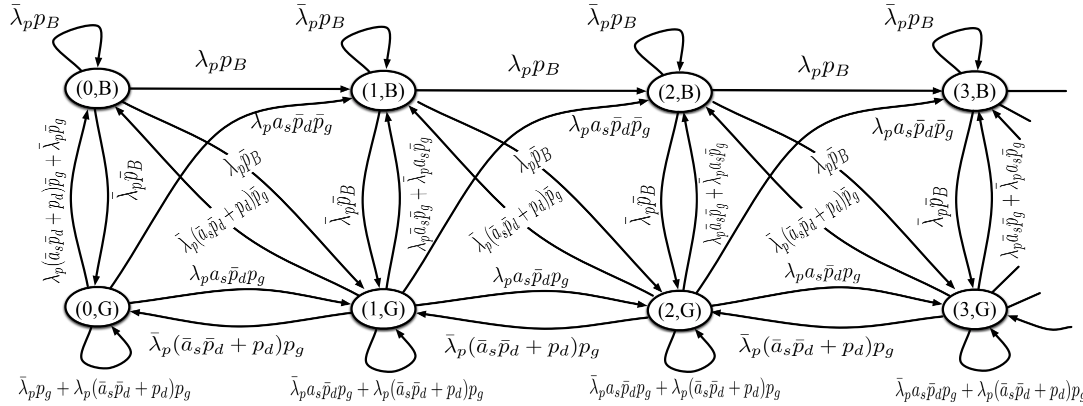

Fig. 3: The PU queue Markov chain model (in this figure, the notation $\bar{q}$ is used to denote $1 - q$)

different expression for the SU throughput as will be explained later.

1) The Transition Probabilities: The Markov chain has two types of states (K, G) and (K, B), where K is the number of PU packets in the queue, G means that the PU's channel is in the good state and B means that the PU's channel is in the bad state. More specifically, we have a Markov chain $\{X(n), n = 0, 1, 2, ...\}$, whose state space is given by S=$\{(K, T) : K = 0, 1, 2, ..., T \in \{G, B\}\}$.

The transitions between states are as follows:

— (K, G) to $(K + 1, G)$: the transition in this case occurs according to the following equation:
$\Pr(X(n + 1) = (K + 1, G) \mid X(n) = (K, G)) =$ Pr((a new packet arrives at the PU queue) ∩ (SU does not detect the PU presence and decides to access the channel) ∩ (the channel in the next time slot remains in the good state))= $\lambda_p a_s(1-p_d)p_g$, where p_d is the detection probability of the spectrum sensor.

— From (K, G) to $(K + 1, B)$: it is same as the above transition but p_g is replaced by $1-p_g$. Therefore the transition probability equals to $\lambda_p a_s(1 - p_d)(1 - p_g)$.

— The rest of the transition probabilities are shown in Fig. 3 and can be deduced easily.

2) The Steady State Distribution Calculation: We start by calculating the steady state distribution of the Markov chain shown in Fig. 3 so that we can get an expression for the SU throughput of the three systems.

The steady state distribution vector is given by

$$\mathbf{v} = [\pi_0^G, \pi_0^B, \pi_1^G, \pi_1^B, ...].$$

Define the vector $\mathbf{v}_k = \begin{pmatrix}\pi_k^G \\ \pi_k^B\end{pmatrix}$. Note that $\mathbf{v}_0 = \begin{pmatrix}\pi_0^G \\ \pi_0^B\end{pmatrix}$. The state transition matrix of the Markov chain shown in Fig. 3 can be written as

$$\Phi = \begin{pmatrix} B & A_0 & 0 & 0 & \dots \\ A_2 & A_1 & A_0 & 0 & \dots \\ 0 & A_2 & A_1 & A_0 & \dots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}, \qquad (2)$$

where B, A_0, A_1, A_2 are shown in equation (3) at the top of the next page. The state transition matrix Φ is a block-tridiagonal matrix; therefore the Markov chain shown in 3 is a homogeneous quasi birth-and-death (QBD) Markov chain. The steady state distribution of the Markov chain shown in Fig. 3 satisfies the following equation [12]:

$$\mathbf{v}_k = \mathbf{R}^k \mathbf{v}_0, \quad k > 0, \qquad (4)$$

where the rate matrix $\mathbf{R}$:

$$\mathbf{R} = \begin{pmatrix} r_{11} & r_{12} \\ r_{21} & r_{22} \end{pmatrix},$$

which is the solution of the following equation

$$A_2 + (A_1 - I_2)R + A_0 R^2 = 0_{2\times 2}, \qquad (5)$$

which can obtained by substituting equation (4) in the next equation

$$\mathbf{v}_k = A_2 \mathbf{v}_{k-1} + A_1 \mathbf{v}_k + A_0 \mathbf{v}_{k+1}, \quad k \geq 1, \qquad (6)$$

Equation (6) can be easily derived using the states balance equations.
By solving equation (5), the matrix R is obtained as follows:

$$r_{11} = \frac{a_s \lambda_p (1 - p_d)}{(1 - \lambda_p)(a_s p_d - a_s + 1)}$$

$$r_{12} = \frac{\lambda_p}{(1 - \lambda_p)(a_s p_d - a_s + 1)}$$

$$r_{21} = \frac{a_s \lambda_p (1 - p_d)(1 - p_g)}{(1 - \lambda_p)(a_s p_d - a_s + 1)(\lambda_p p_B - pb - \lambda_p + \lambda_p p_g + 1)}$$

$$r_{22} = \frac{B_1}{(1 - \lambda_p)(a_s p_d - a_s + 1)(\lambda_p p_B - pb - \lambda_p + \lambda_p p_g + 1)} \qquad (7)$$

,where $B_1 = \lambda_p(a_s + \lambda - p + p_B - a_s\lambda_p - a_s p_d - a_s p_B - a_s p_g - \lambda_p p_B - \lambda_p p_g + a_s \lambda_p p_d + a_s \lambda_p p_B + a_s \lambda_p p_g + a_s p_d p_B + a_s p_d p_g - a_s \lambda_p p_d p_B - a_s \lambda_p p_d p_g)$
To get the steady state distribution of the Markov chain, the following normalization requirement is applied:

$$\sum_{k=0}^{\infty} (\pi_k^G + \pi_k^B) = 1,$$

$$\mathbf{B} = \begin{pmatrix} (1-\lambda_p) + \lambda_p((1-a_s)(1-p_d)+p_d)p_g & (1-\lambda_p)(1-p_B) \\ (1-\lambda_p) + \lambda_p((1-a_s)(1-p_d)+p_d)(1-p_g) & (1-\lambda_p)p_B \end{pmatrix}.$$

$$\mathbf{A_0} = \begin{pmatrix} (1-\lambda_p)((1-a_s)(1-p_d)+p_d)p_g & 0 \\ (1-\lambda_p)((1-a_s)(1-p_d)+p_d)(1-p_g) & 0 \end{pmatrix}.$$

$$\mathbf{A_1} = \begin{pmatrix} [\lambda_p((1-a_s)(1-p_d)+p_d) + (1-\lambda_p)a_s(1-p_d)]p_g & (1-\lambda_p)(1-p_B) \\ [\lambda_p((1-a_s)(1-p_d)+p_d) + (1-\lambda_p)a_s(1-p_d)](1-p_g) & (1-\lambda_p)p_B \end{pmatrix}.$$

$$\mathbf{A_2} = \begin{pmatrix} \lambda_p a_s(1-p_d)p_g & \lambda_p(1-p_B) \\ \lambda_p a_s(1-p_d)(1-p_g) & \lambda_p p_B \end{pmatrix}. \tag{3}$$

and using equation (4),we have

$$\bar{\mathbf{1}} \left(\sum_{k=0}^{\infty} \mathbf{R}^k \right) \mathbf{v}_0 = 1, \text{where } \bar{\mathbf{1}} = [1 \quad 1].$$

$$\text{So, } \bar{\mathbf{1}} \left(\sum_{k=0}^{\infty} \mathbf{R}^k \right) \mathbf{v}_0 = \bar{\mathbf{1}}(\mathbf{I}_2 - \mathbf{R})^{-1} \begin{pmatrix} \pi_0^G \\ \pi_0^B \end{pmatrix} = 1,$$

where $\mathbf{I}_2$ is the 2×2 identity matrix. The relationship between π_0^G and π_0^B has to obtained so the previous equation will be in one variable only. To get the relationship between π_0^G and π_0^B, the balance equations around $(0, G)$ and $(0, B)$ are solved. The balance equation around state $(0, G)$ is given by:

$$\begin{aligned} &[a_s \lambda_p p_g - p_g - a_s \lambda p_d p_g + 1]\pi_0^G \\ &= (1-\lambda_p)((1-a_s)(1-p_d)+p_d)p_g \pi_1^G \\ &+ (1-\lambda_p)(1-p_B)\pi_0^B. \end{aligned} \tag{8}$$

The balance equation around state $(0, B)$ is given by:

$$\begin{aligned} &[\lambda_p + (1-\lambda_p)(1-p_B)]\pi_0^B = \\ &(1-\lambda_p)((1-a_s)(1-p_d)+p_d)(1-p_g)\pi_1^G \\ &+ [(1-\lambda_p)(1-p_g) + \lambda_p((1-a_s)(1-p_d)+p_d)(1-p_g)]\pi_0^G. \end{aligned} \tag{9}$$

Eliminating π_1^G from equation (8) and (9), we obtain the relation between π_0^G and π_0^B as

$$\pi_0^B = \frac{(1-p_g)\pi_0^G}{\lambda_p p_B - p_B - \lambda_p + \lambda_p p_g + 1}. \tag{10}$$

π_0^G is obtained as in equation(11).

$$\pi_0^G = \frac{a_s p_d - 2\lambda_p - p_B - a_s + a_s p_B + \lambda_p p_B + \lambda_p p_g - a_s p_d p_B + 1}{(1-\lambda_p)(p_B + p_g - 2)(a_s p_d - a_s + 1)}. \tag{11}$$

Secondary Throughput Analysis:

The closed-form expressions of the SU throughput of the baseline systems and the proposed system are derived as follows:

— **Baseline system 1**: PU has no CQI feedback. Therefore, the PU always accesses the channel when it has packets in its queue even if the channel is in the bad state. Moreover, the SU accesses the channel with access probability a_s in every time slot if it does not detect the PU's presence. Therefore, the SU transmits its packets with no PU collisions only in the PU empty states $(0, G)$, when the PU does not recieve new packet in this time slot and $(0, B)$. Hence, the SU throughput in this system, μ_{s1}, is given by

$$\mu_{s1} = a_s(1-p_f)(1-\lambda_p)[\pi_0^G + \pi_0^B],$$

where p_f is the false alarm probability of the spectrum sensor.

— **Baseline system 2**: In this system, only the PU has access to the CQI feedback, so the SU accesses the channel in the good and bad CQI states with an access probability a_s if the SU does not detect the PU's existence. The PU does not transmit packets in the bad channel states. Thus, the SU succeeds in transmitting a packet in the (K, B) states with probability a_s, as the PU will be backing-off. Also, the SU succeeds in transmitting a packet with probability a_s if the PU channel is in the empty good state, i.e., $(0, G)$ and the PU does not receive new packet in this time slot. Moreover, the SU has to detect the PU's absence. Hence, the SU throughput in this system, μ_{s2}, is given by

$$\begin{aligned} \mu_{s2} &= a_s(1-p_f)[(1-\lambda_p)\pi_0^G + \sum_{k=0}^{\infty} \pi_k^B] \\ &= a_s(1-p_f)[(1-\lambda_p)\pi_0^G + [0 \quad 1](\mathbf{I}_2 - \mathbf{R})^{-1} \begin{pmatrix} \pi_0^G \\ \pi_0^B \end{pmatrix}] \\ &= \frac{a_s(p_f - 1)(a_s + \lambda_p - a_s p_d - 1)}{a_s p_d - a_s + 1}. \end{aligned}$$

— **The proposed system**: In this system, the SU has access to the PU CQI feedback; therefore, the SU accesses the channel with probability 1 under bad PU CQI feedback, where the PU is backing off. However, under good PU CQI feedback the SU accesses the channel with probability a_s if the SU decides that the PU is absent. Therefore, the SU transmits its packets collision-free in the bad states (K, B) with probability 1 and in the empty good state, $(0, G)$, with probability a_s. Hence, the SU throughput in this system, μ_{s3}, is given by,

$$\begin{aligned} \mu_{s3} &= a_s(1-p_f)(1-\lambda_p)\pi_0^G + \sum_{k=0}^{\infty} \pi_k^B \\ &= a_s(1-p_f)(1-\lambda_p)\pi_0^G + [0 \quad 1](\mathbf{I}_2 - \mathbf{R})^{-1} \begin{pmatrix} \pi_0^G \\ \pi_0^B \end{pmatrix}. \end{aligned}$$

The closed-form expressions of the SU throughput of the-first baseline systems and the proposed system are very long so they are omitted due to the lack of space.

Primary Delay Analysis:

In this subsection, we derive an expression for the average PU packet delay for the baseline systems and the proposed system using Little's law as follows:

$$D_p = \frac{E(Q_p)}{\lambda_p} = \frac{1}{\lambda_p}\sum_{k=0}^{\infty} k(\pi_k^G + \pi_k^B)$$

$$= \frac{1}{\lambda_p}[1 \quad 1]R(\mathbf{I}_2 - \mathbf{R})^{-2}\begin{pmatrix}\pi_0^G\\ \pi_0^B\end{pmatrix},$$

where D_p is the average PU packet delay, and $E(Q_p)$ is the average number of packets in the PU queue. The closed-form expressions of the average PU packet delay of the two baseline systems and the proposed system are so long so they are omitted.

3) Access Probabilities Calculation: The access probability a_s has to be selected to maximize the secondary throughput, μ_{si}, $i = 1, 2, 3$, while keeping the PU queue stable. The problem can be formulated as follows.

$$\max_{a_s} \quad \mu_{si}$$

subject to

$$\pi_0^G > 0 \text{ and } \pi_0^B > 0.$$

By differentiating the expression of μ_{si} with respect to a_s and equating the derivative to zero, the optimal access probability a_s^* can be obtained. For all systems, the differentiation of μ_{si} with respect to a_s results in a second degree polynomial in a_s. Therefore, there are two solutions of this maximization problem. The solution in the range from 0 to 1 is selected as the value of a_s that results in the maximum secondary user throughput will always guarantee the stability of the PU queue; since if this a_s causes the PU queue to be unstable, this will reduce the SU throughput since the SU will never transmit any packets in the good channel states, as the PU queue will always be backlogged. The maximum secondary throughput is obtained by substitution of a_s^* in the equation of μ_{si} to get the maximum secondary throughput, μ_s^{max}.

The closed-form expressions of the access probabilities to maximize the secondary throughput of the baseline systems and the proposed system are as follows,

— **Baseline system 1**: $a_s^* = \frac{p_B + \sqrt{\lambda_p(p_B-1)(p_B+p_g-2)}-1}{p_d+p_B-p_dp_B-1}$.

— **Baseline system 2**:$a_s^* = \frac{\sqrt{\lambda_p - 1}}{p_d - 1}$.

— **The proposed system**: $a_s^* = \frac{p_B + \sqrt{\lambda_p(p_B-1)(p_B+p_g-2)}-1}{p_d+p_B-p_dp_B-1}$.

It can be noticed that the first baseline system and the proposed system have the same expression for the access probabilities to maximize the secondary throughput of each of them.

B. The Perfect Sensing CQI Feedback Based-Access System

In this subsection, we provide the analysis of the PU's queue for the perfect sensing CQI feedback based access system. In this system, the PU has a CQI feedback and the SU has an access to this PU CQI feedback. The SU accesses the PU channel in the bad channel states with probability 1. When the PU channel is in the good state and the PU's queue is empty, the SU accesses the channel with probability 1 as well (because of perfect sensing). The Markov chain of the CQI feedback perfect sensing system is also a two-dimensional Markov chain, which is shown in Fig. 4. The analysis of this Markov chain is done using the same steps used in the above Markov chain, shown in 3. Therefore, we can get the steady state distribution as follows:

$$\pi_0^G = \frac{\lambda_p p_B - p_B - 2\lambda_p + \lambda_p p_g + 1}{(\lambda_p - 1)(p_B + p_g - 2)}. \tag{12}$$

$$\pi_0^B = \frac{(1-p_g)\pi_0^G}{\lambda_p p_B - p_B - \lambda_p + \lambda_p p_g + 1}. \tag{13}$$

$$\mathbf{R} = \begin{pmatrix} 0 & \lambda_p/(1-\lambda_p) \\ 0 & \frac{\lambda_p(\lambda_p + p_B - \lambda_p p_B - \lambda_p p_g}{(1-\lambda_p)(\lambda_p p_B - p_B - \lambda_p + \lambda_p p_g + 1).} \end{pmatrix} \tag{14}$$

The SU throughput for this system μ_{sp}, can be calculated using the following expression:

$$\mu_{sp} = (1-\lambda_p)\pi_0^G + \sum_{k=0}^{\infty}\pi_k^B$$

$$= (1-\lambda_p)\pi_0^G + [0 \quad 1](\mathbf{I}_2 - \mathbf{R})^{-1}\begin{pmatrix}\pi_0^G\\ \pi_0^B\end{pmatrix}.$$

The closed form expression of the SU throughput can be shown in the following equation:

$$\mu_{sp} = \begin{cases} 1-\lambda_p, & \text{if } \lambda_p < \zeta_B - 1. \\ \zeta_B, & \text{otherwise.} \end{cases} \tag{15}$$

C. Performance Results

In this section, a comparative study in terms of the SU throughput of the proposed scheme, the baseline systems, and the perfect sensing CQI feedback based access system, which is an upper bound system, is provided. We also compare the PU delay for the proposed scheme and the two baseline systems.

In Fig. 5 and Fig. 6, the SU throughput is plotted against the PU arrival rate for the different access schemes. In Fig. 5 and Fig. 6, the steady state probability of the channel being in the bad state equals 0.4 and 0.125, respectively, which can be obtained using equation (1). It is clear that the proposed scheme has the highest performance below the perfect sensing CQI feedback based access system since the SU exploits the PU CQI feedback to efficiently access the primary network. Regarding the two baseline systems, it is expected that the performance of the second system is better than the performance of the first one. The PU in the second

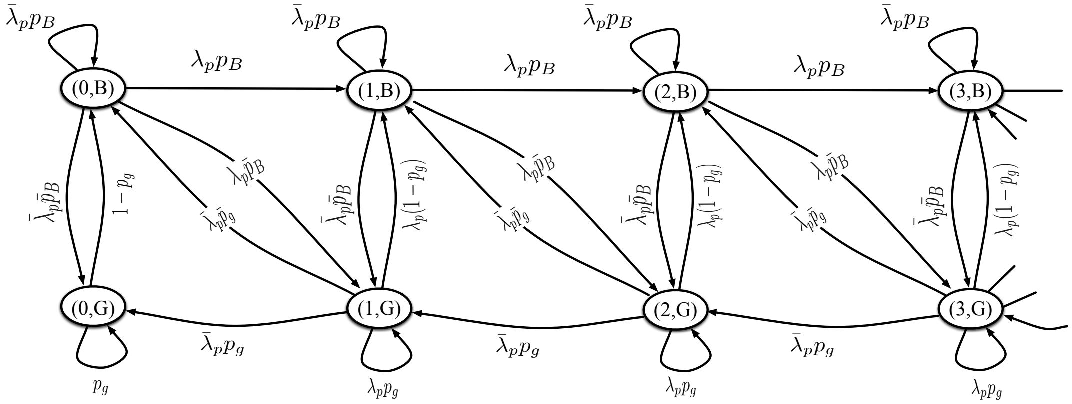

Fig. 4: The PU queue Markov chain model for the perfect sensing CQI feedback based-access system

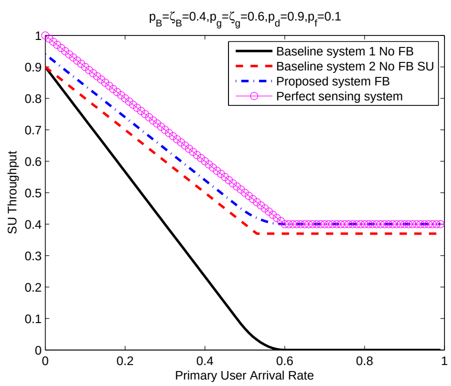

Fig. 5: The SU throughput for different access schemes

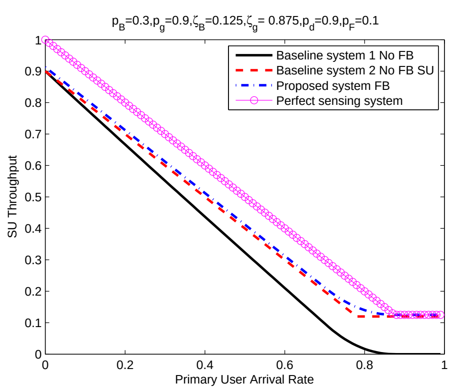

Fig. 6: The SU throughput for different access schemes

system has additional information about the channel state, so the PU does not transmit its packets if the channel is in the bad state, which gives the SU more opportunities to access the channel. However, PU in the first system has no CQI feedback so it transmits its packet independent of channel state.

Moreover, in Fig. 5 and Fig. 6, it is noticed that for the proposed scheme the secondary throughput does not tend to zero as the PU arrival rate goes to 1, unlike the first baseline systems. The minimum value of the SU throughput in the proposed scheme equals the steady state probability of the PU channel being in the bad state, since this minimum level of SU service is always guaranteed (as in the bad states, the PU will be backing-off and the SU will access the channel, collision-free, with probability 1). It can be seen that the SU throughput remains constant after a certain PU's arrival rate. After this PU's arrival rate, the PU's queue is unstable so it always has packets to transmit, however, this does not affect the SU service rate since in this case the SU only accesses the channel when the PU's channel in the bad state.

In Fig. 7 and Fig. 8, the SU optimal access probabilities are plotted against the PU arrival rate for different access schemes, for a steady state probability of the channel being in the bad state of 0.4 in Fig. 7 and 0.125 in Fig. 8. It can be noticed that the second baseline system has the highest optimal access probabilities, which are greater than or equal to one for all values of the PU arrival rate so the maximum access probability equals to one for all values of PU arrival rate. It can be easily shown that the SU service rate is concave in a_s, so setting the values of access probability to one does not affect the optimality if the optimum value of a_s is greater than one. Moreover, the optimal access probabilities in the first baseline system and the optimal access probabilities of the proposed scheme are equal. It is clear that the SU will be less aggressive in accessing the channel under the good channel state in our proposed system as compared to the second baseline system; since, the SU is guaranteed a service rate of 1 under PU bad channel state. For all systems, there will be no access probabilities after a certain value of the PU arrival rate as the PU's queue will be unstable and the SU will be backing-off.

In Fig. 9 and Fig. 10, the PU packet delay are plotted against the PU arrival rate for different access schemes. The PU packet delay in the proposed scheme and the first baseline system are coincident and lower than the second baseline system. It is expected that the proposed scheme improves the PU packet delay due to the CQI awareness at the SU. The SU exploits this additional information to reduce the collisions with the PU and so the PU delay decreases.

IV. Conclusions

In this paper, a CQI feedback based hard decision access scheme for cognitive radio has been developed. The secondary user accesses the channel quality indicator feedback of the

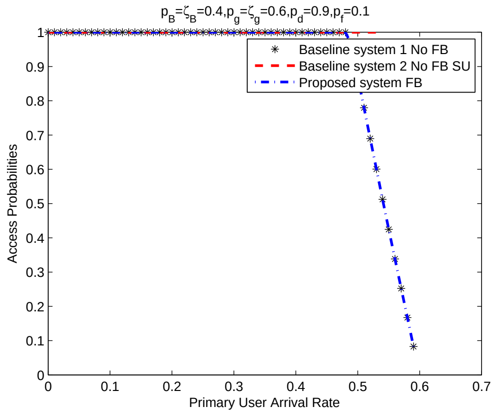

Fig. 7: The SU optimal access probabilities for different access schemes

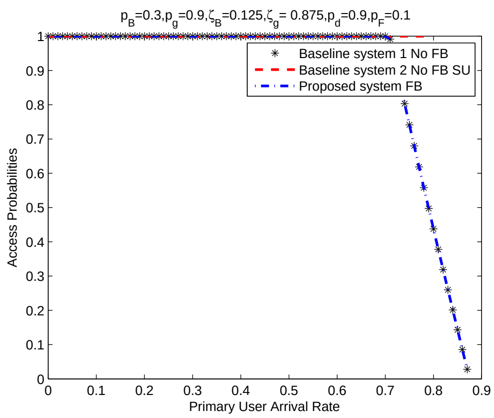

Fig. 8: The SU optimal access probabilities for different access schemes

primary user. The proposed scheme will result in performance improvement by limiting collisions between secondary and primary users. Observing a bad CQI, the primary user backs-off, so the secondary user transmits its packet with fewer collisions with the primary user and this can boost the system performance in terms of secondary throughput and the primary user packet delay.

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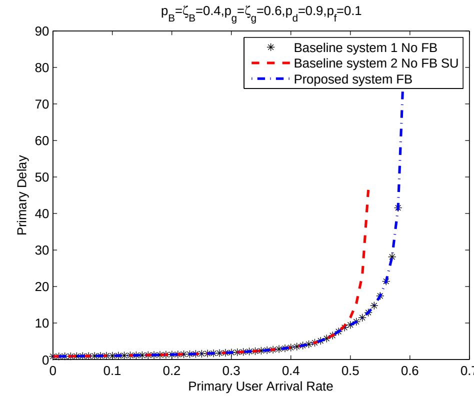

Fig. 9: The PU packet delay for different access schemes

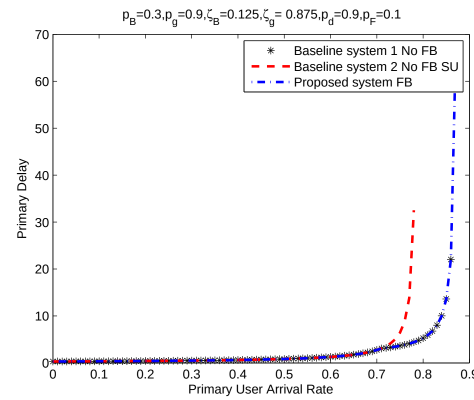

Fig. 10: The PU packet delay for different access schemes

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