International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 13 (2017) pp. 3810-3816

Stability of Queues in Multi-User Cognitive Radios

V.Hamsadhwani
Ph.D.Research Scholar, Department of Electronics and Communication Engineering,
Periyar Maniammai University, Thanjavur,Tamilnadu, India.

Dr. Arun Pachai Kannu
Department of Electrical Engineering, Indian Institute of Technology Madras, Chennai,Tamilnadu India.

Dr. K. Lakshmi
Department of Computer Science and Engineering, Periyar Maniammai University, Thanjavur, India.

Abstract

We study the behavior of Queues in multi-user cognitive radios with several channel sensing order selection strategies. We consider three different mechanisms to resolve contention between cognitive users (CU), COLLISION, BACKOFF and PRIORITY.

For each mechanism, we find the optimal channel sensing order for each CU, which maximizes the total cognitive users' throughput. We also consider a simple cyclic sensing mechanism to sense the channels. Under each channel sensing mechanism, we study the stability of queue for each CU by changing the packet arrival rates of each CU. Our results show that when optimal sensing order is used the stability region is bigger compared to the cyclic sensing order.

Keywords: Cognitive radios, queues, average delay, channel sensing order, stability

INTRODUCTION

With the increase in demand for wireless data, usable RF spectrum is becoming heavily congested and the cognitive radios provide a means for enhancing the efficiency of spectrum usage. A cognitive radio is a smart radio that can intelligently detect available wireless channels in its vicinity and dynamically configure its transmission or reception parameters so as to make the best use of these spectrum holes. Cognitive radios are capable of communicating on licensed spectrum without causing interference to the primary/licensed users of the bands, and therefore hold great potential for improving the efficiency of the usage of licensed spectrum that is otherwise poorly utilized due to static frequency allocations. However, the spectrum that a cognitive radio would be allowed to operate on can be expected to be scattered and heterogeneous in general. In other words, a cognitive radio would need to search over multiple portions of the licensed spectrum, possibly having different bandwidths and primary user characteristics, in order to select the best free channel for its use. Also, these cognitive radios are usually small devices with hardware limitations; they cannot simultaneously sense more than one portion of the spectrum quickly, efficiently and reliably. Hence, each cognitive user (CU) in a cognitive radio network (CRN) would need to have a sensing-order i.e., an order in which it will sequentially sense the different channels until it finds a suitable channel for its communication. In general, each user's data is buffered in the corresponding queue before a suitable channel is selected for transmission. In this work, we study the Queue behavior of multi-user cognitive radio networks with several channel sensing procedures and scheduling mechanisms.

SYSTEM MODEL

We consider a CRN with M cognitive users and N primary channels. We assume that a CU$j \in \{1,2,...,M\}$ can sense not more than one channel at a time, and it therefore has a sensing-order denoted by s^j, $(s^j_1, s^j_2, \cdots, s^j_N)$, which is a permutation of $(1,2,...,N)$. The position of channel i in the sensing-order of CUj is denoted by p^j_i (i.e., $s^j_{p^j_i} = i$).

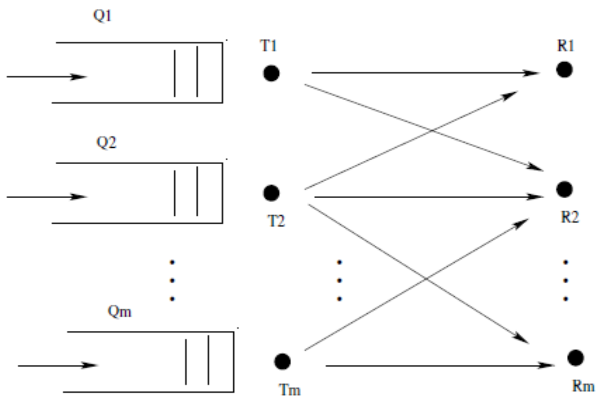

Figure 1: Queues in CRN

The CRN uses a time-slotted structure, similar to that used in [1]–[3], whereby time is partitioned into slots of fixed duration T.

In any given time slot, channel i is either free of primary users with probability θ_i or occupied by primary users with probability ($1-\theta_i$). We refer θ_i as the *primary-free probability* of channel i and is assumed to be known based on prior statistical knowledge. We label the channels 1,2,...,N in descending order of their primary-free probabilities, i.e., $\theta_1 > \theta_2 > ... > \theta_N$. Let $\theta = (\theta_1, \cdots, \theta_N)$ denote a vector of primary-free probabilities. We assume that the primary busy/free states of the different channels are constant over any given time slot. Also, these time slots are independent of each other, and the duration of the time slot change independently across time slots.

Let γ_i^j denote the instantaneous SNR seen on channel i by CUj. In general, CUs employ rate adaptation with $r(\gamma)$ being the data rate for a given SNR γ. Here $r(\cdot)$ is a nondecreasing function. When the CUs do not use rate-adaptation, they use a constant rate R such that $r(\gamma) = R$ irrespective of the channel SNR value.

In general, CUj will consider accessing i^{th} channel in its sensing order only if

$\gamma^j_i > \Gamma^j_i$ where Γ^j_i is the chosen stopping threshold.

Let Qj denote the (buffer) Queue containing the data corresponding to CUj. Let the data arrive at Qj with rate λj and we do not assume any particular probability distribution for data arrival. For convenience, we collect the arrival rates of all users in a vector as $\lambda = [\lambda_1, \cdots, \lambda_M]$. Let $q_j(t)$ denote the number of packets in Q_j at the beginning of t^{th} time slot. If $v_j(t)$ and $b_j(t)$ denote the data arrived and transmitted (successfully) during the t^{th} slot, we have $q_j(t+1) = q_j(t)+v_j(t)-b_j(t)$.

CHANNEL SENSING AND SCHEDULING

Let τ denote the *sensing duration* i.e., the time required to sense one channel with the desired accuracy. If a CU needs k sensings to find a suitable channel for its transmission, the total sensing duration is $k\tau$ and hence, the time available for data transmission is $T-k\tau$. A summary of the slot structure is illustrated in Figure 2.

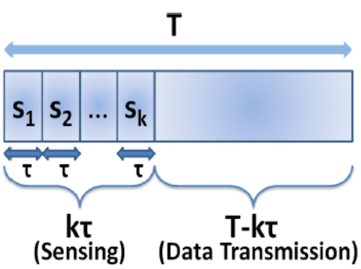

Figure 2: Sensing and data transmission

The *effectiveness* of transmission in a slot, as defined in [1] and [2], is the ratio of the data transmission duration to the total slot duration. If a CU stops sensing and starts transmitting data after k sensings, the effectiveness c_k is defined as

$$c_k \triangleq \frac{T-k\tau}{T} = 1 - \frac{k\tau}{T} \qquad (1)$$

A. *Channel Sensing Process*

CUs perform channel sensing in t^{th} time slot as described below:

- CUj performs channel sensing in t^{th} time slot only if $q_j(t) \neq 0$.
- CUj senses primary channels one by one as per the order given in s^j until a suitable free channel is found.
- CUj selects i^{th} channel in its order for data transmission if s^j_i is free from primary and other CUs and the instantaneous SNR in i^{th} channel is above the stopping threshold, i.e., $\gamma_j{}^i(t) > \Gamma_j{}^i$.
- If two or more CUs choose the same channel for data transmission at the same time, then they perform contention resolution among themselves. At the end of contention resolution, one or more CUs may proceed with data transmission and others may continue to perform channel sensing.

If CUj starts successful data transmission after sensing k channels in t^{th} slot, then the amount of data sent is $b_j(t) = \min(q_j(t), c_k r(\gamma^j_k(t)))$.

B. *Contention Resolution Mechanisms*

We consider the following three contention resolution mechanisms to resolve contentions whenever two or more CUs decide to access the same channel simultaneously.

1) BACKOFF: Each CU uses a backoff mechanism to avoid a possible collision (similar to the ones used in IEEE 802.3 for Ethernet and IEEE 802.11 for Wireless LAN [4]). One CU wins and transmits in the channel for the remainder of the time slot, while the other CUs, who fail in the contention, continue to sense the further channels according to their respective sensing-orders.

2) PRIORITY: Each CU is assigned a priority level just for the purpose of contention resolution. Whenever (and only when) there is a contention, the CU with the highest priority among the contending users gets to transmit until the end of the slot, while the other CUs continue their search for another free channel.

3) COLLIDE: Each contending CU transmits in the channel until the end of the slot. As a result, a collision happens and none of them earn any reward in that slot.

C. Optimal Sensing-Orders without Rate-Adaptation

Let a_i denote the binary availability of channel i i.e. $a_i = 1$ if channel i is primary-free and $a_i = 0$ if it is primary-busy. Let $a \triangleq (a_1, a_2, ... a_N)$ denote a channel availability combination of the N channels. Since the primary-busy/free states of the different channels have been assumed to be independent of each other, we can write the probability of a given channel availability combination a as follows

$$P\{a\} = \prod_{i=1}^{N} \left[a_i \theta_i + (1 - a_i)(1 - \theta_i) \right] \qquad (2)$$

When the CUs do not use rate-adaptation, the total sum throughput of CUs for a given set of sensing-orders $\{s_j\}^M_{j=1}$ can be computed by listing down all (2^N) possible channel availability combinations, determining the sum-throughput for each combination, and computing an expectation of the sum-throughputs over all possible channel availabilities. We illustrate this by means of an example. Let us consider a 5-channel, 3-user CRN. Let the sensing-orders of the 3 CUs be $s^1 = (1,4,3,2,5)$, $s^2 = (2,4,5,1,3)$ and $s^3 = (3,5,4,1,2)$ respectively, and let $a = (0,0,1,1,1)$.

Note that $P\{a\} = (1 - \theta_1)(1 - \theta_2)\theta_3\theta_4\theta_5$. In the first round of sensing, CUs 1 and 2 will sense channels 1 and 2 respectively to be busy, while CU3 will sense channel 3 to be free and use it for transmission for the remainder of the slot to earn a throughput of c_1R. In the second round of sensing, both CU 1 and CU2 will sense channel 4 to be free.

- If COLLIDE is the CRS being used, both CUs will transmit on channel 4 for the remainder of the slot, and hence, collide and earn zero reward. Therefore, the sum throughput under COLLIDE is just c_1R.
- If PRIORITY is used, and if CU1 has higher priority than CU2, then CU1 will get to transmit on channel 4 and earn a throughput of c_2R, while CU2 will continue sensing and sense channel 5 to be free and use it for its transmission to earn a throughput of c_3R. Therefore, the sum-throughput would be $(c_1 + c_2 + c_3) R$. On the other hand, if CU2 has higher priority than CU1, then CU2 will get to transmit on channel 4 and earn a throughput of c_2R while CU1 will end up transmitting on channel 5 to earn a throughput of c_5R. The sum-throughput would therefore be $(c_1 + c_2 + c_5) R$.
- If BACKOFF is used, one of CUs 1 and 2 will win the contention. If CU1 wins the contention (with probability =0.5), by similar arguments as for PRIORITY, CUs 1 and 2 earn throughputs of c_2R and c_3R respectively, whereas if CU2 wins the contention (with probability = 0.5), the corresponding rewards are c_5R and c_2R. The (expected) sum-throughput for this case is therefore $c_1R + ½(c_2R + c_3R) + ½ (c_2R + c_5R) = (c_1 + c_2 + ½c_3 + ½c_5) R$.

The cognitive throughput for the above-mentioned choices for $\{s_j\}^3_{j=1}$ can be obtained by repeating the above procedure for all $2^5 = 32$ possible choices for a and then finding the expectation of the sum-throughput.

We also consider a simple sensing-order selection mechanism, which we refer as cyclic sensing order. First CU chooses the sensing order in the descending order of primary-free probabilities, and the other CUs perform a cyclic shift of the previous CU's sensing order.

For N = 5, with 3 CUs, we have $s^1 = (1,2,3,4,5)$,

$s^2 = (2,3,4,5,1)$, $s^3 = (3,4,5,1,2)$ (referred to as cyclic sensing-orders). Apart from simplicity, cyclic sensing order has its own merits. In case of $N \geq M$, cyclic sensing order ensures that no two (or more) CUs will sense the same channel at the same time and hence avoid the need for contention resolution between CUs altogether. Also, s^1 is the optimal sensing order for single CU user case when there is no rate adaptation [1].

STABILITY OF QUEUES

We have the following notion to define stability of queues. Queue Q_j is called unstable if $\lim_{t\to\infty} q_j(t) = \infty$. We refer that a queue is stable if it is not unstable. CRN system is referred as stable if queues of all CUs in CRN is stable, i.e., Q_j is stable for all $j \in \{1,\cdots,M\}$. Stability region S is defined as the set of all the possible arrival rates λ for which CRN is stable, i.e., $S = \{\lambda : Q_j \text{ is stable } \forall j\}$.

In this section, we study the stability region for various contention resolution mechanisms under different sensing order selection mechanisms.

A. Collision Model

We consider the case of $M = 2$ and $N = 4$. We consider both optimal sensing orders and cyclic sensing orders with collision model for contention resolution. We normalize the data rate as $R = 1$ and slot duration as $T = 1$. We increase the arrival rates λ_1 and λ_2 from 0 to 1 in steps of 0.01. For each pair (λ_1, λ_2) we study the behaviour of Q_1 and Q_2 using simulations over 10000 slots. Q_j is declared unstable if $q_j(10000) > B$ for a suitably chosen threshold B.

In order to understand and quantify the behaviour of the stability region, we introduce the following notions. A point (a,b) with $a > 0$ and $b > 0$ is called admissible if all the points (x,y) with $x \leq a$ and $y \leq b$ are stable.

An admissible point (a,b) is called a corner point if either (c,b) or (a,d) is not admissible for any $c > a$ and $d > b$. Within the stability region S, the largest rate supported for the first user λ_1^{max} while supporting non-zero rate for second user is obtained as $\lambda_1^{max} = \text{argmax}_{(x,y)\in C}\, x$ where C denote the set of corner points. Similarly, we can obtain $\lambda_2^{max} = \text{argmax}_{(x,y)\in C}\, y$. Maximum total throughput within admissible region is obtained as $T_{max} = \max_{(x,y)\in C}\, x + y$. Largest rectangular area

A_{max} within stability region is obtained as $A_{max} = \max_{(x,y)\in C} xy$. Figure 3 and 4 show the stability region for optimal sensing orders and cyclic sensing order respectively for sensing duration $\tau = 0.2$; Small blue squares indicate the region where both Q_1 and Q_2 are stable, green circles indicate the grid points in which only one of the queues is stable and big brown circles indicate the region where both queues are unstable. Figure 5 shows the stability region for optimal sensing orders with longer sensing duration $\tau = 0.25$.

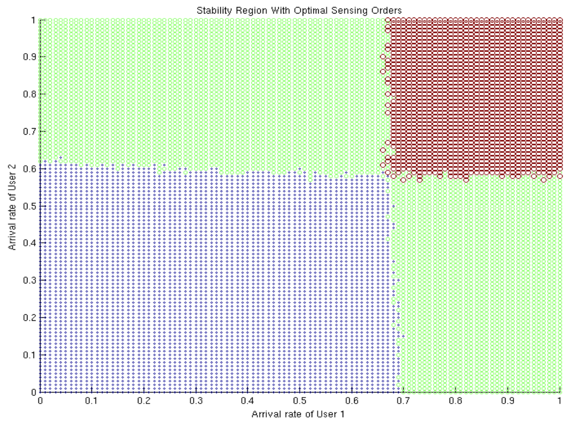

Figure 3: Optimal sensing orders for θ = (0.75, 0.55, 0.4, 0.3), τ = 0.2.

The following inferences can be made from the above plots;

1) For τ = 0.2, with optimal sensing orders, $A_{max} = 0.56*0.66 = 0.3696$, $T_{max} = 0.56+0.66 = 1.22$, while for cyclic sensing orders, $A_{max} = 0.58*0.63 = 0.3654$, $T_{max} = 1.21$. Since optimal sensing orders maximize sum throughput, T_{max} is higher compared to that of cyclic sensing order. As an indirect consequence, optimal sensing orders have larger rectangle within its stability region compared to cyclic sensing orders.

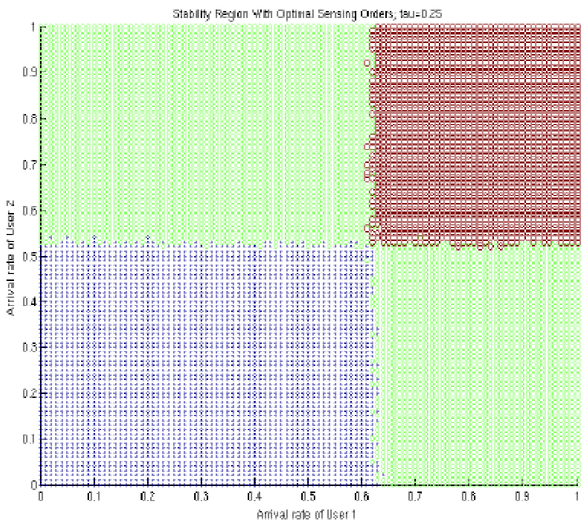

Figure 4: Optimal sensing orders for θ=(0.75, 0.55, 0.4, 0.3), τ = 0.25.

2) For τ = 0.2, with optimal sensing orders, $\lambda_1^{max} = 0.69$, $\lambda_2^{max} = 0.61$, while for cyclic sensing orders $\lambda_1^{max} = 0.71$, $\lambda_2^{max} = 0.62$. When arrival rate of User2 is very small, User1 experiences almost negligible contention for resources from the second user. Since s^1 in cyclic sensing order is optimal in maximizing throughput of a single user CRN, λ_1^{max} of cyclic sensing order is higher than that of optimal sensing order.

3) When the sensing duration τ increases, the amount time for data transmission decreases correspondingly. Hence the stability region (and the associated parameters A_{max}, T_{max}, λ_1^{max}, λ_2^{max}) are smaller in Fig.5 compared to that of Fig.3.

We simulate a 4-channel, 2-user CRN with the following loading scenarios for the channels (where a higher loaded channel is one that carries a higher volume of higher volume of primary traffic and hence has a lower primary-free probability).

i. All channels are lightly loaded

($\theta_1 = 0.95$, $\theta_2 = 0.90$, $\theta_3 = 0.85$, $\theta 4 = 0.80$).

ii. All channels are heavily loaded

($\theta_1 = 0.45$, $\theta_2 = 0.40$, $\theta_3 = 0.35$, $\theta 4 = 0.30$).

The optimal sensing orders and the cyclic sensing orders consisting of the intuitive sensing order (descending order of channels based on their primary-free probabilities) and its cyclic shifts are considered.

Figure 5 shows the plots of maximum sum throughput calculated for increasing values of τ in both lightly loaded channels and heavily loaded channels using optimal sensing orders and cyclic sensing orders in Collision Model.

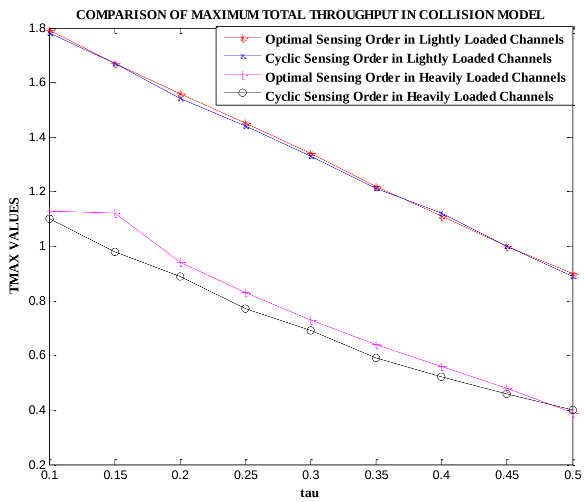

Figure 5: Comparison of Maximum sum throughput Collision Model

When the channels are all lightly loaded, we see that the optimal sensing orders and the cyclic sensing orders result in near-optimal performance. This shows that when

(i) all the channels are lightly loaded, minor differences in their primary-free probabilities do not greatly affect the performance.

(ii) all channels are heavily loaded, we see that the effect of minor differences in the primary-free probabilities is more pronounced.

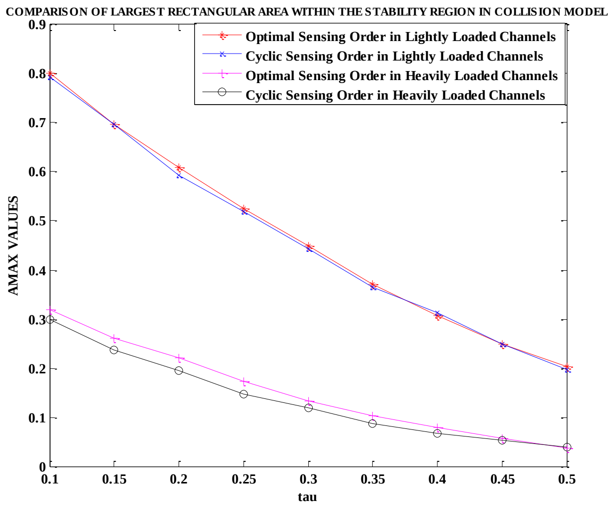

Figure 6: Comparison of Stability Region area in Collision Model

As the value of τ increases, the maximum sum throughput values decrease and when τ = 0.5 the throughput values is the same with both the optimal sensing orders and the cyclic sensing orders are used.

Figure 6 shows the plots of stability region areas calculated for increasing values of τ in both lightly loaded channels and heavily loaded using optimal sensing orders and cyclic sensing orders in Collision Model. It is seen that when

(i) all the channels are lightly loaded, the very simple cyclic sensing orders perform reasonably close to the optimal sensing orders and even outperform the optimal sensing orders at values of τ ranging from 0.35 to 0.5.

(ii) all channels are heavily loaded, the areas of stability regions are higher when optimal sensing orders are used and become the same at τ = 0.5.

B. Back off Model

Figure7 shows the plots of maximum sum throughput calculated for increasing values of τ in both lightly loaded channels and heavily loaded channels using optimal sensing orders and cyclic sensing orders with the back off mechanism.

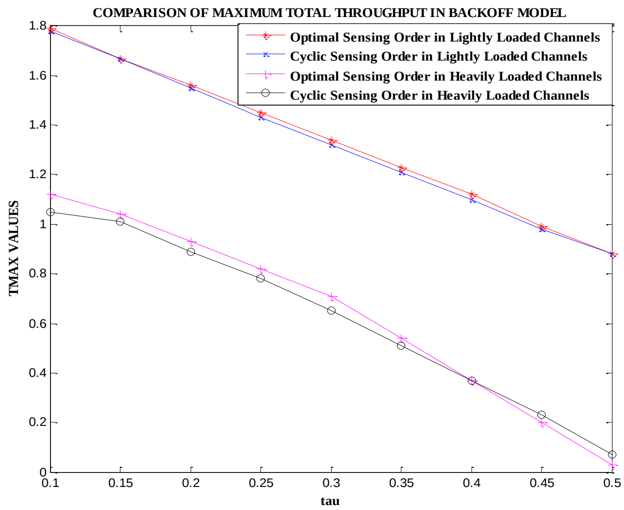

Figure 7: Comparison of Maximum sum throughput Back off Model

The plots of maximum sum throughput calculated for increasing values of τ in both lightly loaded channels and heavily loaded channels using optimal sensing orders and cyclic sensing orders in Back off model is studied.We see that when

(i) all the channels are lightly loaded, the optimal sensing orders and the cyclic sensing orders result in almost the same performance. This shows that when all the channels are lightly loaded, minor differences in their primary-free probabilities not only do not greatly affect the performance, but also the sensing orders too do not alter the sum throughput values.

(ii) all the channels are heavily loaded, the effect of differences in the primary-free probabilities is more on the value of throughput. As τ reaches the value of 0.4 the cyclic sensing order gives higher throughput value.

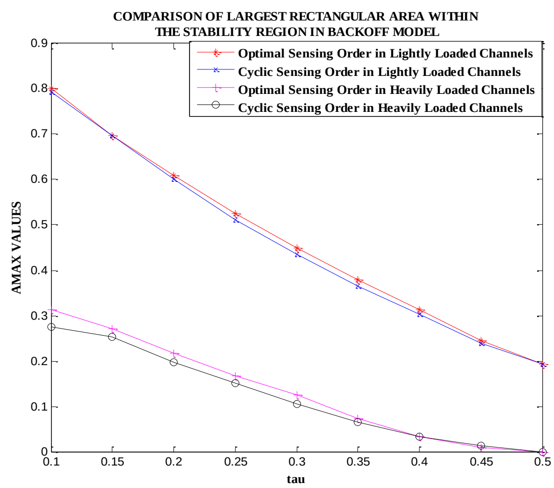

Figure 8: Comparison of Stability Region area Back off Model

Similarly, Figure 8 shows the plots of stability region areas calculated for increasing values of τ in both lightly loaded channels and heavily loaded using optimal sensing orders and cyclic sensing orders using Back off model. It is seen that when

(i) all the channels are lightly loaded, the both cyclic sensing orders and optimal sensing orders perform reasonably close to each other. As the value of τ approaches 0.45, the stability region area values become the same.

(ii) all channels are heavily loaded , the areas of stability regions are larger when optimal sensing orders are used and become almost equal at τ = 0.35.

C. Priority Model

Figure 9 shows the plots of maximum sum throughput calculated for increasing values of τ in both lightly loaded channels and heavily loaded channels using optimal sensing orders and cyclic sensing orders with the priority mechanism. The plot shows that when

(i) all the channels are lightly loaded, with increasing τ values, the cyclic sensing orders have higher maximum throughput values in comparison to the optimal sensing orders. This shows that when all the channels are lightly loaded, minor differences in their primary-free probabilities do not greatly affect the performance.

(ii) all the channels are heavily loaded , optimal sensing orders give higher throughput and perform better.

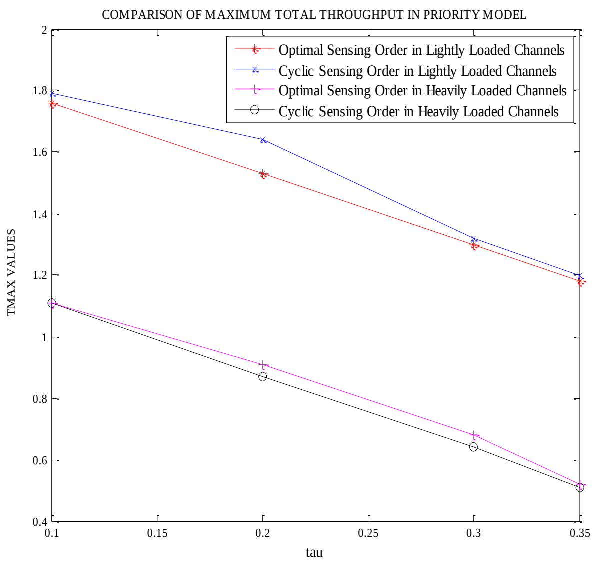

Figure 9: Comparison of Maximum sum throughput Priority Model

Figure 10 shows the plots of stability region areas calculated for increasing values of τ in both lightly loaded channels and heavily loaded using optimal sensing orders and cyclic sensing orders using Priority model. The plot shows that when

(i) all the channels are lightly loaded, we see that the optimal sensing orders result in better performance compared to cyclic sensing orders.

(ii) all channels are heavily loaded, we see that the optimal sensing orders give larger stability areas.

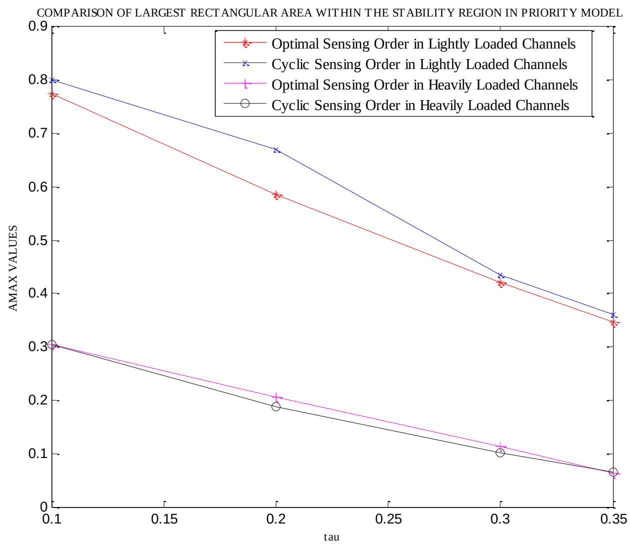

Figure 10: Comparison of Stability Region area Priority Model

CONCLUSIONS

This paper discusses the performance of the queues in multi user cognitive radio networks considering the stability of the queues. The focus is mainly on the comparison of the maximum sum throughput obtained when the channels are lightly loaded as well as heavily loaded with both cyclic sensing and optimal sensing orders. Also the comparison of the stability region areas is carried and our results show that the stability region is larger most of the times when optimal sensing order is used for channel sensing when compared to the cyclic sensing order.

REFERENCES

[1] H. Jiang, L. Lai, R. Fan, and H. V. Poor, "Optimal selection of channel sensing order in cognitive radio," IEEE Transactions on Wireless Communications, vol. 8, no. 1, pp. 297–307, 2009.

[2] R. Fan and H. Jiang, "Channel sensing-order setting in cognitive radio networks: A two-user case," IEEE Transactions on Vehicular Technology, vol. 58, no. 9, pp. 4997–5008, 2009.

[3] H. T. Cheng and W. Zhuang, "Simple channel sensing order in cognitive radio networks," IEEE Journal on Selected Areas in Communications, vol. 29, no. 4, pp. 1–13, 2011.

[4] M. Fruth, "Probabilistic model checking of contention resolution in the IEEE 802.15.4 low-rate wireless personal area network protocol," in International Symposium on Leveraging Applications of Formal Methods, Verification and Validation, pp. 290–297, 2006.

[5] Misra, R., & Kannu, A. P. (2012, December). "Optimal decentralized sensing-orders in multi-user cognitive radio networks" in Global Communications Conference (GLOBECOM), 2012 IEEE (pp. 1447-1452). IEEE.

[6] E. Hossain, D. Niyato and Z. Han, "Dynamic Spectrum Access and Management in Cognitive Radio Networks", Cambridge Univ. Press, 2009.

[7] Y. Zeng, Y. C. Liang, A. T. Hoang and R. Zhang, "A Review on Spectrum Sensing for Cognitive Radio: Challenges and Solutions", EURASIP Journal on Advances in Signal Proc., vol. 2010, Article ID 381465, 2010.

[8] N. B. Chang and M. Liu, "Optimal channel probing and transmission scheduling for opportunistic spectrum access", Proc. 13th ACM Annu.Int. Conf. MobiCom, Montreal, QC, Canada, pp. 2738, Sep. 2007.

[9] H. Kim and K. G. Shin, "Fast discovery of spectrum opportunities in cognitive radio networks", Proc. IEEE Symp. New Frontiers DySPAN, Chicago, IL, Oct. 2008.

[10] Z. Zhang and X. Xie, "Intelligent cognitive radio: Research on learning and evaluation of CR based on Neural Network", ITI 5th Intl. Conf. on Information and Communications Technology, pp. 33–37, Dec. 2007.

[11] H. White and L.S. Christie, "Queuing with Preemptive Priorities or with Breakdown", Operations Research, vol. 6, no. 1, pp. 79–95, Jan.-Feb.1958.

[12] N K Jaiswal, "Preemptive Resume Priority Queue", Operations Research, vol. 9, no. 5, pp. 732–742, Sep.-Oct. 1961.

[13] M. Fruth, "Probabilistic Model Checking of Contention Resolution in the IEEE 802.15.4 Low-Rate Wireless Personal Area Network Protocol", Second International Symposium on Leveraging Applications of Formal Methods, Verification and Validation, pp. 290–297, Nov. 2006.

[14] P. Zhu, J. Li and X. Wang, "Scheduling Model for Cognitive Radio", 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, pp. 1–6, May 2008.

[15] M. Kartheek, R. Misra and V. Sharma, "Performance analysis of data and voice connections in a cognitive radio network", National Conference on Communications, pp. 1–5, Jan. 2011.