Performance Analysis of Data and Voice Connections in a Cognitive Radio Network

M. Kartheek
Department of ECE
Indian Institute of Science
Bangalore, India
Email: kartheek@ece.iisc.ernet.in

Rakesh Misra
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
Email: ee06b097@ee.iitm.ac.in

Vinod Sharma
Department of ECE
Indian Institute of Science
Bangalore, India
Email: vinod@ece.iisc.ernet.in

***Abstract*—We study the performance of cognitive (secondary) users in a cognitive radio network which uses a channel whenever the primary users are not using the channel. The usage of the channel by the primary users is modelled by an ON-OFF renewal process. The cognitive users may be transmitting data using TCP connections and voice traffic. The voice traffic is given priority over the data traffic. We theoretically compute the mean delay of TCP and voice packets and also the mean throughput of the different TCP connections. We compare the theoretical results with simulations.**

***Keywords*: Cognitive radio, performance analysis, TCP traffic, voice traffic.**

I. Introduction

Due to proliferation of new standards and services in wireless communications, there is a scarcity of bandwidth. However recent studies [7], [9] indicate that most of the spectrum licensed to different service providers is often under-utilized. Thus, Cognitive Radios (CR) ([8]) provide a viable solution to the problem of scarce bandwidth by allowing the cognitive (secondary) users, who do not own the spectrum, to use the spectrum when the licensed (primary) users are not using it. For this, the cognitive radio network needs to sense the spectrum ([26]) to see when it is free and then to allocate it efficiently to the secondary users so that their quality of service (QoS) requirements are met. Spectrum sensing has been extensively studied recently (see [13], [15], [26] and the references therein). Spectrum allocation, also referred to as spectrum management, has received comparatively lesser attention.

Dynamic spectrum access ([20]) is broadly classified into dynamic licensing and dynamic sharing. Dynamic sharing can be horizontal and vertical. The vertical sharing can be done via overlay or underlay. Vertical sharing via overlay is the most commonly discussed scenario in cognitive radios and is the topic of concern in this paper. This involves the secondary users sharing a channel when the primary is not using it. The sharing should be done such that the QoS of all secondary users is met. The decision making for spectrum sharing can be distributed or centralized ([20]). In IEEE 802.22 standard, the first to be designed specifically for cognitive radios, a Base station (BS) centrally decides the spectrum allocation. For allocation it can use various approaches: cognitive MAC [14], pricing and game theory ([12], [18]), user cooperation and coordination.

Our study is complementary to the above mentioned work in the sense that it can be used to provide the utility/cost functions needed in these approaches to eventually provide the QoS to the end user. We derive closed-form expressions for the QoS parameters for different applications supported by the CR network when one primary channel is available. We consider two predominant applications, data (via TCP connections) and voice. It is assumed that an efficient spectrum sensing algorithm informs the CR network when the channel is free. We derive approximations for the mean throughput for TCP connections and the average delay for the voice connections in the CR network. Obtaining exact expressions for these quantities are intractable (see [2], [6], [17], [19], [22], and [24] for theoretical models on TCP). One advantage of our approach (as against the TCP studies mentioned) is that it uses simple approximations which are very robust to the primary and secondary system statistics. We have used such approximations before ([3], [23]) and found them quite accurate.

Our setup can be considered as a basic building block in CR networks. Thus the results obtained here will be useful when there are multiple primary channels and/or the cognitive network traffic traverses multiple hops.

There are very few studies providing QoS parameters (e.g., mean delay, packet loss probability) for cognitive radio users. In [25] the ON-OFF periods of the primary channel are modelled as independent, geometrically distributed. The secondary users share the channel via p- persistent CSMA. Throughput and mean delay of the secondary users carrying Poisson traffic are computed. In [10] the ON-OFF periods of the primary are modelled by the busy and idle periods of M/GI/1 queue. Our ON-OFF model is same. However, unlike our case, the secondary users in [10] share the channel via random access and they do not consider TCP traffic. In [16] CBR traffic and best effort traffic are considered and ON and OFF periods are exponentially distributed. They compute the mean delay of the CBR traffic. In [11] connection oriented primary and secondary networks are considered. They

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compute the blocking probabilities and dropping probabilities of the secondary network.

Our contribution is in computing the throughput and mean delays when traffic in the CR network is carried by multiple TCP and CBR connections. Most of the data in real world is carried by TCP connections which use window flow control and behave very differently from other traffic models.

The paper is organized as follows. Section-II describes the basic setup of a cognitive radio network. In Section-III we study the performance of a single TCP connection in the cognitive radio network and compute its throughput. In Section-IV we obtain the throughput for multiple TCP connections. In Section-V we provide mean delay for a voice connection. In Section-VI we obtain the mean delays and the TCP throughput of the data and the voice connections sharing the cognitive network. Section VII concludes the paper.

II. Model Description

We consider a primary network having license for one frequency band and a cognitive radio network. Primary users can transmit data at any time whereas the cognitive radio users opportunistically access the licensed spectrum when it is not being used by the primary network. The primary channel undergoes transition between two states, ON (BUSY) and OFF (IDLE). If the channel is not utilised by any of the primary users then we say that it is in the IDLE state, else it is in the BUSY state. The durations of BUSY and IDLE periods form independent, and identically distributed ($i.i.d.$) sequences, although a BUSY period may have dependence on its next IDLE period. We assume that the state of the channel is known to the CR system via some spectrum sensing algorithm.

One possible scenario for the above setup is as follows. A primary user generates packets and stores in a queue for transmission on the channel. The inter-generation time of the packets form an $i.i.d.$ sequence with arrival rate λ_p packets/sec. The transmission times of the packets also form an $i.i.d.$ sequence with s_p a generic transmission time. We assume $\rho_p = \lambda E[s_p] < 1$; otherwise there will be no spare bandwidth for the CR network. The queue length process for the primary queue forms a renewal process with arrivals seeing an empty queue as the renewal epochs. The BUSY periods, IDLE periods and the BUSY periods together with the next IDLE periods each form $i.i.d.$ sequences. When the primary channel is in the IDLE state, the cognitive radio users use the primary channel till the primary users again start transmission.

The above scenario is a queueing system with two GI/GI/1 queues (primary and CR) and a single server (Fig 1). The packets in the primary queue have preemptive priority over the packets in the CR queue. We ignore the overheads due to the fragmentation of the CR packets (thus leading to a queueing system with preemptive-resume service). In this setup we compute the throughput and the mean delays of packets arriving in the CR queue.

Our analysis will be useful in many other scenarios where an approximation of the primary channel occupancy can be modelled by $i.i.d.$ sequences of ON-OFF periods (e.g., when

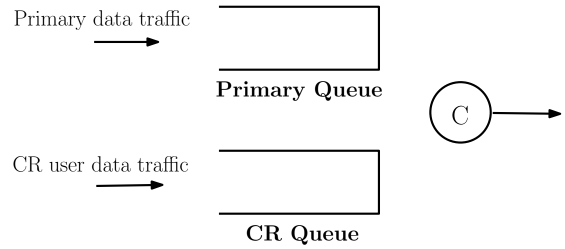

Fig. 1. Basic queue model of a cognitive radio network.

the primary network may be a Wi-Fi or a cellular network). The secondary system could possibly be using a IEEE 802.22 based system. Then the BS detects the channel availability via some distributed cooperative spectrum sensing algorithm. The BS may use the channel in Time Division Duplex fashion. Then for the downlink it can combine all the data and real time traffic appropriately to transmit on the channel. An advantage of the queueing model in Fig 1 is that then we can use various results available in queueing theory to get appropriate approximations. If we approximate the queues in Fig 1 by M/GI/1 queues, which we will often do, then the distribution of the BUSY and the IDLE periods of the primary channel are available [1]. This is the ON-OFF model used in [25] also. Thus we can choose λ_p and s_p so as to approximate ON-OFF periods in other scenarios and then use our results to get the performance of secondary users in those scenarios.

III. Throughput for a Single TCP Connection

First we consider a single TCP connection in the CR network. Generalization to multiple TCP connections will be considered in the next section. For simplicity we assume the TCP connection to be persistent, transmitting a long file. Results can be extended to other scenarios. Also we assume that a TCP packet or its ack can be lost/in-error with probability q independently of other events. For a wireless channel this is a realistic assumption and q depends on the wireless channel state, transmission power and the receiver noise power. These are independent of the other quantities considered in this paper. The packet lengths of the TCP connection are assumed to form an $i.i.d.$ sequence with a general distribution and a finite mean (often the packet lengths of a TCP connection are constant). Let a generic TCP packet has length L_T and let C be the capacity (in bits per sec) of the channel. Then, the mean service time of a TCP packet is $E[s_T] = E[L_T]/C$. We compute the mean throughput of the TCP connection which is its main QoS parameter.

Let C_T denote the time taken by a TCP packet in the CR queue to complete its service which includes its own service time and the time taken to serve the primary packets which arrive during this period (due to preemptive priority to primary traffic, these packets will be served before completion of service of the current TCP packet). Approximating the mean number of primary packets arriving during the service of the TCP packet with $\lambda_p E[C_T]$ (this holds if primary arrivals are

Poisson), we get,

$$E[C_T] = E[s_T] + \lambda_p E[C_T] E[s_p]$$

and hence,

$$E[C_T] = \frac{E[s_T]}{1-\rho_p}. \tag{1}$$

If we approximate the primary queue by an M/GI/1 queue then in [23] we have shown that the TCP connection will have a stationary distribution.

We compute λ_T the throughput obtained (in packets/sec) for the TCP connection. Let Δ be the total propagation delay in the network including for the acks. Also let $E[W_q]$ be the time stationary TCP window length when its packets/acks are lost with probability q.

We use the approximation developed in [3] [4] where it has been shown to work well. We approximate the CR queue by an M/GI/1 queue. However its arrival rate is obtained by taking into account the TCP dynamics (in particular the closed loop window flow control). Since the primary queue has preemptive priority over the CR queue, the mean sojourn time of the CR packets can be given as (if we approximate the primary queue also by an M/GI/1 queue)

$$E[S_T] = \frac{\lambda_p E[s_p^2] + \lambda_T E[s_T^2]}{2(1-\rho_p)(1-\rho_p-\rho_T)} + \frac{E[s_T]}{(1-\rho_p)}, \tag{2}$$

where $\rho_T = \lambda_T E[s_T]$ (see [5]). Thus we can approximate the throughput of the TCP connection as

$$\begin{aligned} \lambda_T &\approx \frac{E[W_q]}{E[S_T]+\Delta} \qquad (3)\\ &= \frac{E[W_q]}{\frac{\lambda_p E[s_p^2]+\lambda_T E[s_T^2]}{2(1-\rho_p)(1-\rho_p-\rho_T)} + \frac{E[s_T]}{(1-\rho_p)} + \Delta}(packets/sec). \end{aligned}$$

The above equation is an algebraic equation with a unique positive solution which provides us the TCP throughput. We can obtain the throughput if we know the time stationary mean window size $E[W_q]$.

For independent packet loss case, various approximations for $E[W_q]$ for new Reno version of TCP are available in [3], [21], [4] which we will use in the following.

We generalize these results to multiple TCP connections in the next section. We will also verify the accuracy of our results via simulations.

IV. Throughput for Multiple TCP Connections

In this section we consider the scenario where the cognitive radio users have multiple TCP connections sharing the channel when the primary is not using it. The packets of the TCP connections are buffered in the CR queue and transmitted in the First Come First Serve (FIFS) fashion whenever the channel is available. This is one possible scenario where the CR system has a Base Station which is transmitting to different users on its downlink. We obtain the expressions for the throughput of the TCPs.

We use the following notation in our analysis. There are N long-lived TCP connections. For the i^{th} TCP connection, $\Delta(i)$ is the total propagation delay, L_i is the packet length (assumed $i.i.d.$ for each connection, independently of another) and $E[s_i] = E[L_i]/C$ is the mean service time. Packets of the i^{th} TCP connection are dropped independently with probability q_i. Let $E[W_q(i)]$ be the time stationary mean window size and $E[n_i]$ the mean number of packets at the CR queue (including the packets being transmitted) for the i^{th} TCP connection. We obtain the $E[W_q]$ via the approximations mentioned in the last section. Let $\lambda_T(i)$ be the stationary throughput obtained (in packets/sec) for the i^{th} TCP connection. We approximate the primary queue as well as the CR queue by M/GI/1 queues. We justify the approximation by comparing the results with simulations. We use the notation of the previous subsection. The mean packet arrival rate λ_T, mean service time $E[s_T]$ and the second moment of the service time distribution $E[{s_T}^2]$ of the CR queue are given by

$$\begin{aligned} \lambda_T &= \sum_{i=1}^{N} \lambda_T(i), && (4)\\ E[s_T] &= \sum_{i=1}^{N} \frac{\lambda_T(i)}{\lambda_T} E[s_i], && (5)\\ E[{s_T}^2] &= \sum_{i=1}^{N} \frac{\lambda_T(i)}{\lambda_T} E[{s_i}^2], && (6)\\ \rho_T &= \lambda_T E[s_T]. && (7) \end{aligned}$$

The mean sojourn time of a packet in the CR queue is ([5])

$$E[S_T] = \frac{\lambda_p E[s_p^2] + \lambda_T E[s_T^2]}{2(1-\rho_p)(1-\rho_p-\rho_T)} + \frac{E[s_T]}{(1-\rho_p)}. \tag{8}$$

We approximate the mean sojourn time of packets of each TCP connection by (8). Then the throughput of the i^{th} TCP connection is given by

$$\lambda_T(i) = \frac{E[W_q(i)]}{E[S_T]+\Delta(i)}(packets/sec). \tag{9}$$

Plugging (9) into (8) we obtain a nonlinear equation of order $2N$. Solving this gives $E[S_T]$. Then from (9) we directly obtain $\lambda_T(i), i = 1, ..., N$.

We use QualNet simulations to verify the accuracy of above approximations.

The primary ON-OFF occupancy is modelled via a GI/GI/1 queue where the interarrival times have a truncated Pareto distribution with mean 40 ms and the packet sizes are $i.i.d$ uniformly distributed with mean 1500 bytes. The capacity of the primary channel is 1Mbps.

We consider 2 TCP connections for a cognitive radio network which have packet lengths of 1000 bytes and 1500 bytes, and W_{max} of 8 and 10 respectively. We obtain the throughputs for each TCP connection for different propagation delays and packet loss probabilities and tabulate the results in Table I and Table II. We see that our theory predicts the throughput of the two TCP connections quite accurately for different propagation delays and packet loss probabilities.

Connection	Δ (msec)	Simulation Throughput (kbps)	Theoretical Throughput (kbps)
TCP1	0	234.45	236.24
TCP2	0	449.61	442.68
TCP1	50	234.44	234.12
TCP2	50	449.57	439.48
TCP1	200	180.79	185.25
TCP2	100	497.52	478.17
TCP1	150	201.405	205.90
TCP2	100	478.99	455.47
TCP1	100	201.40	208.69
TCP2	50	479.05	462.77
TCP1	200	238.27	247.50
TCP2	300	340.27	333.60

TABLE I
THROUGHPUT OF MULTIPLE TCPS IN A CR NETWORK

Connection	Δ (msec)	q	Simulation Throughput (kbps)	Theoretical Throughput (kbps)
TCP1	100	0.01	320.60	304.62
TCP2	150	0.06	240.20	259.21
TCP1	100	0.005	275.50	287.50
TCP2	150	0.025	372.47	371.31
TCP1	100	0.02	150.55	156.83
TCP2	150	0.03	355.89	367.00
TCP1	200	0.01	168.42	175.39
TCP2	100	0.005	481.96	465.77
TCP1	200	0.008	192.32	200.66
TCP2	100	0.02	440.03	420.81

TABLE II
THROUGHPUT OF MULTIPLE TCPS IN A CR NETWORK WITH PACKET LOSS

V. MEAN DELAY OF A CBR CONNECTION

We consider a primary network with one primary channel and one or more CBR connections between cognitive radio users. Other details and notation remains same. Average end-end delay is the sum of the mean sojourn time of a packet in the queue and the propagation delay. Hence we calculate the mean sojourn time of the CBR packets. We approximate the primary queue and the CR queue as M/GI/1 queues and obtain the performance measure. The approximation is justified by comparing with the simulation results. The approximations improve as the number of CBR connections increases.

Let the total mean packet arrival rate of the CBR packets be λ_C, mean service time of the CBR packet be $E[s_C]$, and $\rho_C = \lambda_C E[s_C]$. We assume that $\rho_C + \rho_p < 1$ The mean sojourn time of CBR packets, $E[S_C]$ is given by

$$E[S_C] = \frac{\lambda_p E[s_p^2] + \lambda_C [s_C^2]}{2(1-\rho_p)(1-\rho_p-\rho_C)} + \frac{E[s_C]}{(1-\rho_p)}. \qquad (10)$$

We will compare this approximation with the simulation results in the next section.

VI. DATA AND VOICE TRAFFIC

Consider a primary network with one primary channel and both TCP and CBR connections used by the cognitive radio users. We use the same notation as before. The CBR packets are given priority over TCP packets. This is because the CBR traffic is real time. Also, since QoS of TCP connections (even real time) is mainly decided by their mean throughput, giving priority to CBR does not affect the performance of TCP connections (as long as there is enough bandwidth for the overall CR traffic) but the CBR (delay and probability of packet loss, not considered here) QoS can substantially improve. In [23] we have shown that this overall system (with primary and CBR approximated by Poisson streams) has a unique stationary distribution and that the system converges to the stationary distribution from any initial conditions.

Connection	Δ (msec)	Simulation Throughput (kbps) end-end delay(msec)	Theoretical Throughput (kbps) end-end delay(msec)
TCP1	0	159.624	161.310
TCP2	0	159.635	161.310
TCP3	0	159.633	161.310
CBR delay	0	19.45	20.6
TCP1	50	164.480	164.070
TCP2	100	149.860	153.95
TCP3	50	164.537	164.070
CBR delay	50	69.18	70.6
TCP1	100	171.14	170.550
TCP2	150	159.094	159.640
TCP3	200	148.620	150.04
CBR delay	150	169.08	170.6
TCP1	250	155.168	154.860
TCP2	150	178.679	176.800
TCP3	300	144.945	145.81
CBR delay	250	269.26	270.6

TABLE III
THRUOGHPUT OF TCPS AND AVERAGE END-END DELAY OF CBR TRAFFIC IN A CR NETWORK FOR $q = 0$

The sojourn time of CBR packets remains same as in equation (10) (since CBR is not given preemptive priority, its performance is slightly worse than provided by (10)). Now for the TCP throughput we can consider only scenario 3.

In obtain the TCP throughput we approximate the primary queue by an M/GI/1 queue and the TCP and CBR flows as Poisson arrivals. Hence we obtain the mean sojourn time of TCP packets as

$$\begin{aligned} E[S_T] = \; & \tfrac{\lambda_p E[s_p^2] + \lambda_C E[s_C^2] + \lambda_T E[s_T^2]}{2(1-\rho_p-\rho_C)(1-\rho_p-\rho_C-\rho_T)} \\ & + \tfrac{E[s_T]}{(1-\rho_p-\rho_C)}, \end{aligned} \qquad (11)$$

where, $E[s_T]$ and $E[{s_T}^2]$ are obtained from (6) and (7). The overall throughput of the TCP connections is given by

$$\lambda_T = \frac{E[W_q]}{E[S_T] + \Delta} (packets/sec). \qquad (12)$$

These equations can be used along with (7)-(9) (instead of (8)) to obtain the throughput of different TCP connections.

A. Simulation Results

We consider the same setting for primary as before. CBR rate is 200 kbps, and there are 3 TCP connections. TCP packet lengths are 1500 bytes and $W_{max} = 10$ for all TCPs.We obtain the throughputs for TCP connections and average end-end delay for the CBR packets for different propagation delays and packet loss probabilities. We compare the results with the simulations using QualNet. The results are provided in Table III and Table IV.

q	Connection	Simulation Throughput (kbps)	Theoretical Throughput) (kbps)
0.001	TCP1	162.234	160.430
	TCP2	161.869	160.430
	TCP3	161.542	160.430
0.0025	TCP1	161.868	160.320
	TCP2	161.623	160.320
	TCP3	160.95	160.320
0.005	TCP1	161.748	159.980
	TCP2	161.608	159.980
	TCP3	159.537	159.980
0.01	TCP1	159.389	159.290
	TCP2	160.271	159.290
	TCP3	156.310	159.290
0.02	TCP1	153.765	157.614
	TCP2	153.755	157.614
	TCP3	153.745	157.614

TABLE IV

THRUOGHPUT OF TCPS WITH PACKETS DROPPED AND $\Delta = 100msec$ IN A CR NETWORK (MIXED TRAFFIC)

VII. CONCLUSIONS AND FUTURE DIRECTIONS

We have analysed the performance of data and voice connections in a cognitive radio network. There is one primary channel. The occupancy of the primary channel is modelled as an ON-OFF process. We obtain the throughput of cognitive radio users using TCP connections and the mean delay of cognitive voice traffic.

Further work can be done by considering multiple channels and including video traffic.

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