Effect of Dynamic Spectrum Access on Transport Control Protocol Performance

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Abstract— ***Transmission Control Protocol*** **(TCP) is the most commonly used transport protocol on the Internet. All indications assure that it will be an integral part of the future internetworks. In this paper, we present how regular TCP which was designed for wired networks is not suitable for dynamic spectrum access networks. We develop an analytical model to estimate the TCP throughput of Dynamic spectrum access networks. Dynamic spectrum access networks deal with opportunistic spectrum access leading to greater utilization of the spectrum. The extent of utilization depends on the primary user's traffic and also on the way the spectrum is accessed by the primary and secondary users. The proposed model considers primary and secondary user traffic in estimating the TCP throughput by modeling the spectrum access using continuous-time Markov chains, thus providing more insight on effect of dynamic spectrum access on TCP performance than the existing models.**

Keywords- Dynamic Spectrum Access Network, Markov chain, channel, Transport Control Protocol, Throughput.

I. INTRODUCTION

A Dynamic spectrum access/cognitive radio network is an opportunistic network. *Spectrum opportunity* deals with the usage of an available (free) channel that is a part of the spectrum which is not currently used by primary users [1]. The licensed owner of a frequency band is called a *primary user* (PU) and the one who utilizes spectrum opportunities for communication is called a *secondary user* (SU). Secondary users are equipped with cognitive radios to enable them to sense the presence of primary users and tune to the spectrum band (channel) which is not in use at any point of time for its own communication. When the primary user of that channel returns the secondary user is forced to vacate the channel. The secondary user may then shift to another available channel and recover from that state. This is called *spectrum hand-off.*

It is a known fact that TCP is inherently inefficient on wireless networks [2]. TCP was originally designed to work on wired networks. In a wireless environment, packets may get lost due to congestion or corruption of the physical medium. Cognitive networks worsen the situation for the following reasons.

- *Dynamic topology*: As the channel of communication changes, some of the neighbors who were reachable on the previous channel might not be reachable on the current channel and vice versa. As a result the topology of the network changes with the change in frequency of operation resulting in route failures and packet loss.
- *Heterogeneity*: Different channels may support different transmission ranges, data rates and delay characteristics.
- *Spectrum-Handoff delay*: For each transition from one channel to another channel due to the PU's activity, there is a delay involved in the transition called *Spectrum-Handoff delay*.

All these factors decrease the predictability of the cause of transit-delay and subsequent packet loss on the network. The time latency during channel hand-off in cognitive networks might cause the TCP round trip timer to time out. TCP will wrongly recognize the delays and losses due to the above factors as network congestion and immediately take steps to reduce the congestion window size knowing not the cause of packet delay. This reduces the efficiency of the protocol in such environments.

Very few papers have focused on the study and improvement of TCP in Dynamic spectrum access networks. [3] and [4] discuss the transport layer design issues in such networks. [5] studies the performance of TCP flavors over Dynamic spectrum access links using simulations and the analytical model proposed in this work does not consider the effect of primary and secondary user's activity. It assumes the presence of a primary user and the effect of detection error is studied. In this paper we will modify the analytical model proposed in [5] to incorporate the effect of PU and SU traffic on the TCP performance. The PU and SU traffic are modeled using Markov chain and the blocking probability of the SUs is calculated.

Markov chains were used to model dynamic spectrum access networks in [6-10]. Some of them do not capture the important details of dynamic spectrum access networks and some are too complex to be considered for just the throughput study in this paper. [7] proposes a Markov model, but it does not allow for the secondary users to reoccupy another free channel once it has been forced to vacate from a channel and considers the call to be completely dropped. The *spectrum hand-off* capability of the cognitive radio is thus not modeled in this work. [6] tries to reduce the *forced termination* of the secondary radios at the cost of blocking probability by reserving some of the channels for primary user access only. Both of these papers discuss on the optimal reservation of the channels for primary users to reduce the dropping probability and forced termination when in-fact these states can be totally avoided with *spectrum hand-off* capability of a cognitive radio. Analysis in [8-11], does not consider prioritized primary users. [12-13] proposes Markov models to study secondary user contention and obtain fairness among them in a resource sharing environment. In this paper the Markov model proposed in [7] which is sufficiently accurate for this work, has been modified to accommodate the spectrum hand-off capability to capture the dynamic nature of the networks.

The rest of the paper is organized as follows. The system model is described in Section II. The Analytical model for TCP throughput estimation and the Markov model for determining the blocking probability of secondary users are developed in section III. Section IV presents the results and Section V concludes the work.

II. System Model

The system consists of a Base Station (BS), a group of prioritized primary users and opportunistic secondary users as shown in Fig. 1. There a total of N channels in the system. The BS and the SUs scan their radio environment and maintain the information on the availability of channels with a certain confidence level [14]. The detection process is logically performed by a *Scanning Subsystem* of the Link Layer (*SSLL*) [5]. The signal received by the *SSLL* from the PU is affected by noise only, i.e. fading and multi-path effects are not considered.

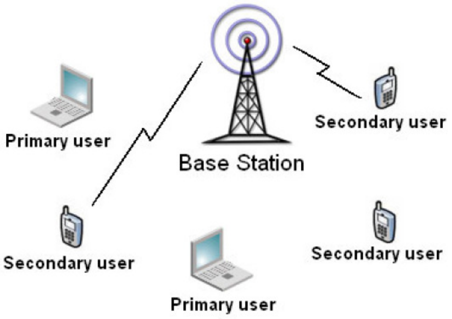

Figure 1. Dynamic spectrum access network with three SUs and two PUs.

When a SU wants to start a communication it sends a request to the BS on a control channel which is dedicated for exchange of control information. After the BS acknowledges an end-to-end communication link is established at the transport layer. Once the communication link has been established, data segments flow to network layer and then to the data link layer.

At the link layer, the free channels are contended for on a frame-by-frame basis. Channels are scanned periodically after fixed intervals [16]. This period of observing the channel is called *scanning phase* (*SP*). It is assumed that the SUs and the BS can scan the complete bandwidth one time in each SP. If a free channel was detected in the *scanning phase*, the *channel access phase* (*CAP*) follows during which the buffered frames are forwarded to the destination. TCP packets are secured by a Link Layer (LL) Stop and Wait ARQ mechanism [17].

If there was no free channel (a blocked state) during the *scanning phase* the *SSLL* has to wait for the next *SP* to scan for a spectrum opportunity. The length of the *scanning phase*, T_i and *channel access phase*, T_o is not necessarily equal, but is the same for individual cycles. The *scanning phase* is not negligible when compared to *channel access phase* in dynamic spectrum access networks. The following derivations are assumed for the TCP steady state, i.e. a long lasting TCP connection with an infinite source of data.

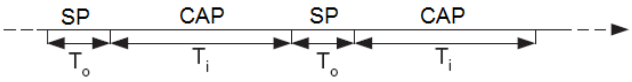

Figure 2. Scanning cycles used by the *SSLL* [5].

III. Analytical Model For TCP Throughput Estimation

In this section we will develop an analytical model to determine the TCP throughput of the SUs in the presence of PUs traffic and detection errors. If we do not take congestion related TCP packet loss into account, and assume a wireless link of infinite accessible capacity, the maximum throughput TCP can achieve depends only on the packet loss probability, segment size and *RTT* [18]. The simple SQRT model for estimating maximum achievable TCP throughput or ('bandwidth') B is shown below. Though there are other TCP throughput analytical models [19][20], we have chosen this formula since it is simple and sufficiently accurate model of TCP.

$$B = \frac{MSS}{RTT}\sqrt{\frac{3}{2p}} \qquad (1)$$

- MSS is the TCP segment size.
- p is the packet error probability. It can be computed as:

$$p = 1 - p_c^{N_F} \qquad (2)$$

where p_c denotes the probability of correct frame reception at LL after at most n_{max} retransmissions. This can be written in a compact form as:

$$p_c = (1 - p_e)\sum_{i=0}^{n_{max}} p_e^i = 1 - p_e^{n_{max}+1} \qquad (3)$$

where p_e denotes the LL frame error rate (FER). Here, we assume that the probability of LL frame error is uniformly distributed over all frames.

- RTT is the TCP packet round-trip time. RTT in the given network scenario can be formulated as [5]:

$$RTT = 2T_{sr} + nT_pN_F + T_o + T_w \qquad (4)$$

- T_{sr} denotes one-way packet delivery time (including transmission, propagation, packet queuing and processing delay).
- n is the average number of LL frame retransmissions. The average number of LL frame retransmissions is given as:

$$n = (1-p_e)\sum_{i=1}^{n_{max}-1} i p_e^i + n_{max} p_e^{n_{max}} \qquad (5)$$

where n_{max} is the maximum number of retransmissions of one LL frame.

- N_F is the number of LL frames per TCP packet.
- T_p is the delay of the ARQ protocol, introduced by LL frame retransmissions.
- T_o is the channel observation time or the scanning time.
- T_w is the average delay that a packet incurs when either the channel is not available or an improper decision is made by the by the scanner. In this paper, we are concerned with the delay (Tw) caused due to unavailability of the channels and detection errors which is derived below.

A. *Estimation of Wait time Tw*

In each individual scan either of the following events will increase the *RTT* by an inter-scanning interval of T_i.

1. A spectrum opportunity may be available or not based on the primary user's traffic. If there is no channel available then the user has to wait until the next scan interval (S) by waiting T_i seconds.
2. When a channel is available, a decision on the availability of the channel may result in an error, thus detecting that the channel is not available.

The average time a TCP packet must wait to gain access to the channel is given by T_W.

$$T_W = \lim_{n\to\infty}\sum_{k=1}^{n}[p_b + p_f(1-p_b)]^k \times T_i$$

$$= \frac{T_i[p_b + p_f(1-p_b)]}{1-[p_b + p_f(1-p_b)]} \qquad (6)$$

where,

$$p_f = \frac{\Gamma\left(WT_o,\frac{v}{2}\right)}{\Gamma(WT_o)} \qquad (7)$$

where p_b is the blocking probability which means that that no channel is free. p_f is the probability of false alarm, i.e. misinterpretation of a free channel as occupied. W is the bandwidth of the PU channel, v is the threshold of the energy detector, and $\Gamma(.,.)$ and $\Gamma(.)$ are upper incomplete gamma and gamma functions, respectively [15], [16]. The model proposed in [16] assumes the absence of PUs. Our model considers PU traffic and takes the effect of probability of detecting the PU on a DSA link, limiting the probability of introducing interference to the PU system by the DSA device.

B. *Markov Model to determine Blocking probability, p_b.*

In this sub-section a Markov model to determine the blocking probability of SU frames is discussed.

There are a total of N channels available for both secondary and primary users. Each channel is assumed to be of equal bandwidth. The PUs traffic in each channel is assumed to follow an ON/OFF pattern. A channel can be accessed by a SU if it is not being occupied by any PU. In this model it is assumed that both the PUs and SUs access the channels randomly. This is explained with the help of Fig. 3. There are a total five channels of which two are occupied by PUs and one by an SU. When a new SU arrives as shown in Fig. 3a, it chooses a random free channel. A PU can choose any random channel and as shown in Fig. 3b, if it chooses a secondary occupied channel, the SU jumps to a different free channel. If there is no other channel available, the SU's service is dropped as shown in Fig. 3c. An SU cannot use a channel if it does not have an opportunity to do so as shown in Fig 3c.

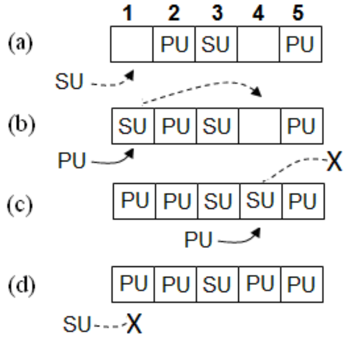

Figure 3. Random access in five channels.

There are four states in this model of which we are aiming to calculate probability of the blocking state. The states are explained from the point of view of secondary users since the paper focuses on the study of capacity of SUs.

Blocking state: When all the channels are occupied and no incoming traffic can be accommodated into the system, then the SU is said to be in Blocked state. On the occurrence of such an event, the SUs have to wait for the next *scanning phase* to scan for a spectrum opportunity.

Dropping state and Transition state: When the primary user of a channel returns during the transmission of the SUs frame, the frame will be corrupted due to interruption. This is considered as collision by the link layer and a retransmission is attempted. Though the probability of occurrence of this event is very low due to the small frame transmission period, it is still considered in model for the sake of accuracy in calculating the blocking probability, p_b.

Non-blocking state: A secondary user is considered to be in this state if its frame has been transmitted successfully without being interrupted by a PU on that channel.

The Markov model for spectrum access with spectrum hand-off is explained in Fig 4. The PU's and SU's traffic is assumed to follow a Poisson arrival process with mean rates λ_p and λ_s respectively. They have a negative exponential service time distribution with mean rate $1/\mu_p$ and $1/\mu_s$ respectively. The numbers i, j, k represent the number of PUs, SUs and the type of state of the secondary user, respectively. Spectrum hand-off is accounted, for example, by letting the state (1, 1, 1) back to (1, 2, 0) and not dropping it. If it were dropped then it has to be sent to (1, 1, 0). *P(i, j, k)* denotes the steady-state probability of state *(i, j, k).*

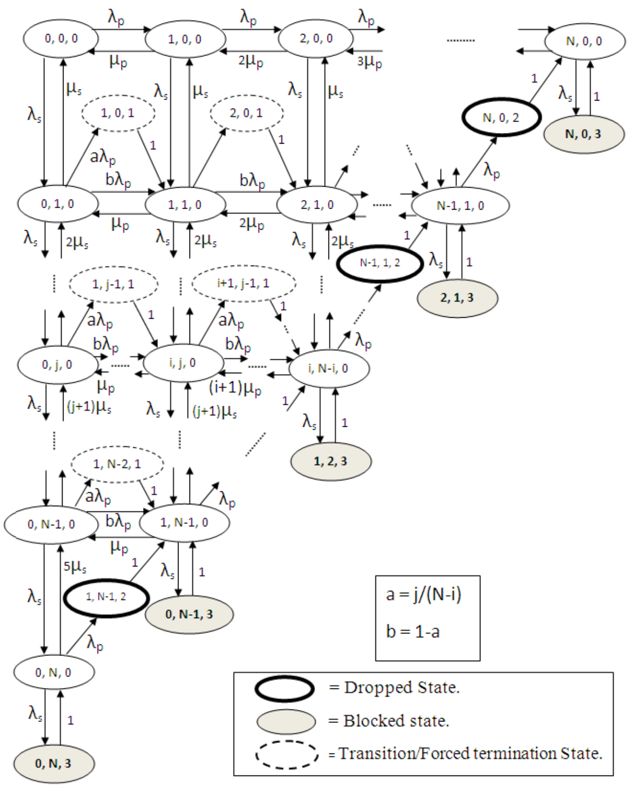

Figure 4. Markov model for dynamic spectrum access network with spectrum hand-off.

The balance equations for this model are given below:
For $i = 0, 0 \leq j \leq (N-1), k = 0,$

$$[j.\mu s + \ i\mu p + \lambda s + \ \lambda p].P(i,j,k) = \ \delta.\lambda s.P(i,j-1,k)$$
$$+(j+1).\mu s.P(i,j+1,k) + (i+1).\mu p.P(i+1,j,k)$$
$$\delta = \ 0 \ for \ j = 0 \ and \ \delta = 1 \ for \ j \neq 0 \tag{8}$$

For $i \neq 0, k = 0, i + j \leq (N-1),$

$$[j.\mu s + \lambda s + \lambda p + i.\mu p].P(i,j,k)$$
$$= \ \delta.\lambda s.P(i,j-1,k) + (j+1).\mu s.P(i,j+1,k)$$
$$+\left(\frac{(N-i-j)}{N-i}\right).\lambda p.P(i-1,j,k)$$
$$+(i+1).\mu p.P(i+1,j,0) + \delta.P(i,j-1,k+1)$$
$$\delta = \ 0 \ for \ j = 0 \ and \ \delta = 1 \ for \ j \neq 0 \tag{9}$$

For $k = i = 0, j = N,$

$$[j.\mu s + \lambda s + \lambda p].P(i,j,k) = \ \lambda s.P(i,j-1,k) + P(i,j,k+2) \tag{10}$$

For $i \neq 0 \neq N, i + j = N, k = 0,$ (11)

$$[\lambda p + \lambda s + i\mu p + j\mu s].P(i,j,k) =$$
$$\lambda s.P(i,j-1,k) + P(i,j,k+2) + \left(\frac{(N-i-j)}{N-i}\right).\lambda p.P(i-1,j,k) + P(i,j-1,k+1) + P(i,j,k+3)\lambda s.P(i,j-1,k) + P(i,j,k+2) + \left(\frac{(N-i-j)}{N-i}\right).\lambda p.P(i-1,j,k) + P(i,j-1,k+1) + P(i,j,k+3)$$

For $j = 0, i = N, k = 0,$

$$[j.\mu p + \lambda s].P(i,j,k) =$$
$$P(i,j,k+3) + P(i,j,k+2) + \lambda p.P(i-1,j,k) \tag{12}$$

For $i + j = N, k = 2,$

$$P(i,j,k) = \ \lambda s.P(i,j,k-2) \tag{13}$$

For $k = 1, i + j \leq N, 1 \leq i \leq (N-1)$

$$P(i,j,k) = \ \lambda p.(\tfrac{j}{N-i})P(i-1,j+1,k-1) \tag{14}$$

For $k = 1, i + j = N, i \neq 0$

$$P(i,j,k) = \ \lambda p.P(i-1,j+1,k-3) \tag{15}$$

Equations (8) to (12) correspond to the non-blocking states. Equation (13) corresponds to the blocked states. Equation (14) corresponds to the transition states and (15) to the dropping states. The final equation is the sum of all probabilities which is,

$$\sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{2} P(i,j,k) = 1 \tag{16}$$

The dropping probability is given by the equation:

$$p_d \ = \sum_{i=1}^{N} \ \sum_{j=0,i+j=N}^{N} P(i,j,2) \tag{17}$$

The blocking probability is given by the equation:

$$p_b \ = \sum_{i=0}^{N} \ \sum_{j=0,i+j=N}^{N} P(i,j,3) \tag{18}$$

Fig 5. shows the variation of blocking probability as a function of PU's arrival rate, λ_p. It can be observed that the dropping probability increases with increase in PU's arrival rate and with decrease in total number of channels, *N*.

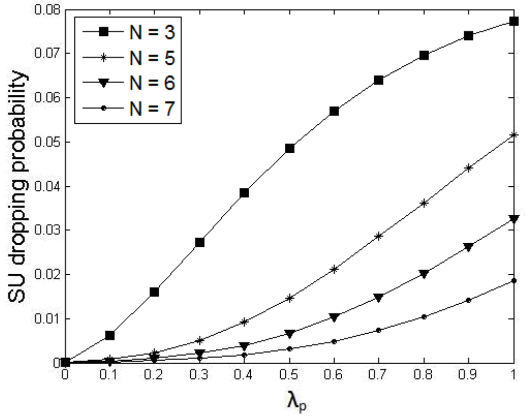

Figure 5. Variation of SU blocking probability as PU's arrival rate is varied for different number of channels.

The value of blocking probability, p_b obtained using eq. 18 using Markov model will be used in the calculation of T_W in eq. 6. In the next section TCP throughput of SUs is studied using this analytical model.

IV. RESULTS AND ANALYSIS

In this section the impact of primary and secondary user traffic as well as number of channels and scanning time on TCP throughput is studied using the proposed analytical model.

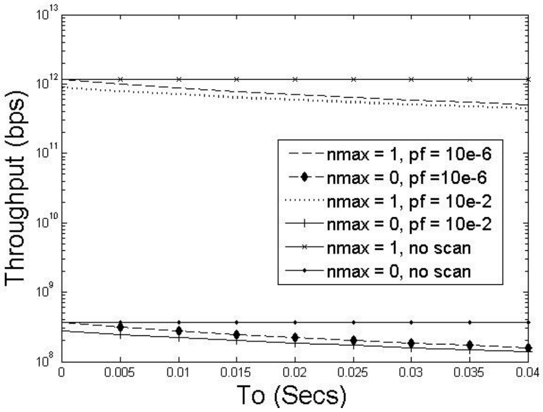

Figure 6. TCP throughput as a function of scanning time. $p_e = 10^{-7}$, $N_F = 2$, MSS = 512 Bytes, $T_{sr} = T_p = 10$ ms, $\lambda_s = \lambda_p = 0.5$, N = 5.

Fig. 6 shows the variation of TCP throughput as a function of scanning time T_o. PU and SU traffic is maintained constant. *No scan* means that it a perfect detection. It can be observed that throughput decreases with increase in scan time. The impact of an incorrect detection is not significant when T_o is large, since the length of the scanning phase is the dominating component for increasing the *RTT*. It can also be concluded that the throughput is always lesser when compared to a *perfect scan* (*no scan*). These results are similar to [5] because the PU and SU traffic rate is maintained at a constant rate for this graph. The actual advantage of the proposed model is that it allows studying the effect of number of channels and PU, SU traffic as shown in the figures below.

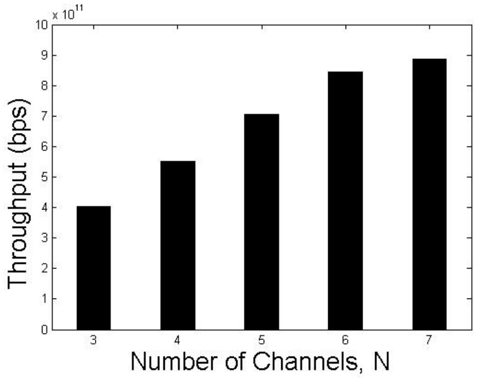

Figure 7. TCP throughput as a function of number of channels. $p_e = 10^{-7}$, $p_f = 10^{-6}$, $n_{max} = 1$, $N_F = 2$, MSS = 512 Bytes, $T_{sr} = T_p = 10$ ms, $\lambda_s = 0.5$.

Fig. 7 shows the variation of throughput as a function of total number of channels *N*. As the number of channels is increased there are more opportunities for a fixed PU and SU arrival rate. As a result the blocking probability p_b of the SU is reduced which in-turn reduces the *RTT*, increasing the overall throughput.

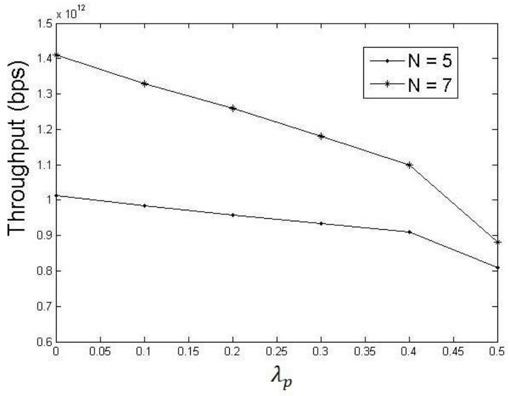

Figure 8. TCP throughput as a function of SU traffic rate, λ_p. $p_e = 10^{-7}$, $N_F = 2$, MSS = 512 Bytes, $T_{sr} = T_p = 10$ ms, $\lambda_s = 0.5$.

Fig. 8 shows the variation of throughput as a function of primary user's traffic. It can be seen that as the PU's traffic is increased, the TCP throughput of the secondary user is reduced. This is due to the fact that with increase in PU traffic, lesser number of channels are available for SUs. As a result, the blocking probability, p_b increases which results in an increase in *RTT* and a decrease in overall TCP throughput. It can also be observed that as the number of channels, *N* is increased the throughput increases and the reasons are similar to the explanations of Fig. 7.

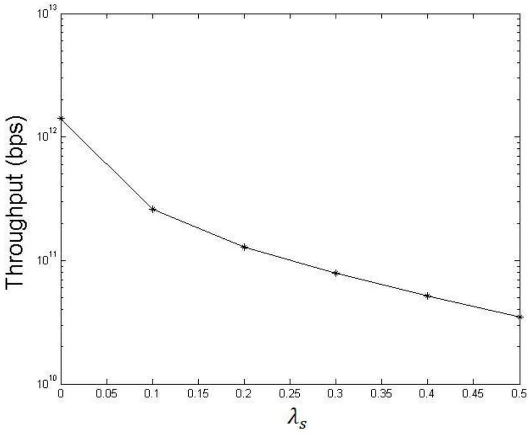

Figure 9. TCP throughput as a function of SU traffic rate, λ_s. $p_e = 10^{-7}$, $N_F = 2$, MSS = 512 Bytes, $T_{sr} = T_p = 10$ ms, $\lambda_p = 0.5$, N = 7.

Fig. 9 shows the variation of TCP throughput as a function of SU traffic. The throughput decreases as the SU traffic increases because of the increased contention between the secondary users. The increase contention leads to increased blocking probability and *RTT* resulting in decreased throughput.

V. CONCLUSION

In this paper, we discussed how regular TCP which was designed for wired networks is not suitable for dynamic spectrum access networks. We modified a simple yet sufficiently accurate TCP model to incorporate the delay caused by primary and secondary user's traffic and detection errors and analyze the throughput of Dynamic spectrum access networks by modeling the spectrum access using continuous-time Markov chains. Simulations were used to visualize the effect of primary and secondary user's traffic, number of channels and the length of the scan period on the performance of TCP throughput. Thus, the proposed analytical model proved to be efficient in capturing the dynamic nature of dynamic spectrum access networks unlike existing models.

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