Adaptive Power Control Policy Using Effective Capacity in Spectrum Sharing Area

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Abstract. In this paper, we propose and analyses a power control policy in terms of maximizing effective capacity at physical and link layers under average interference and transmit power constraint of the cognitive transmitter in spectrum sharing area. The quality of service constraint and proposed power policy in physical layer drives the data queue at link layer to maximize the required statistical quality of service (QoS) of the cognitive users. In this work we also take into account the average transmit power constraint and channel state information at both transmitter and receiver sides. The numerical evaluations are confirmed our theoretical results.

Keywords: Cognitive Radio, Effective Capacity, Power Control, Sharing Spectrum.

1 Introduction

Radio spectrum has become a potentially scarce resource due to increasing wireless equipment. Most of the spectrum is assigned and licensed users have high priority on using the licensed spectrum. Beside, studies show that 85% of the license spectrum is unoccupied in certain geographical locations. For this reason, spectrum utilization is a main and new challenging issue in wireless communication networks [1].

The Cognitive Radio (CR) concept was firstly coined by Mitola to utilize license and license-exempt spectrum [2]. The proposed technology relies on observing its environment and adapting itself to new radio environments by using its collected data without interfering with other users.

In Cognitive Radio technology, in order to utilize spectrum, two techniques are considered; *Opportunistic Spectrum Access* in which the cognitive users are allowed to access their spectrum in order to transmit their information to destination, when primary transmitter is off. The other technique is *Spectrum Sharing* where the cognitive users are allowed to access and use the primary spectrum simultaneously without harming the Primary User (PU) with interference. In this work we place emphasis on the second technique, which means primary and secondary users are allowed to use the same spectrum.

In the proposed spectrum sharing environment, the QoS optimization of the secondary user is considered with respect to the primary user's QoS based on

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interference. Much research effort has been put on maximizing the capacity of the secondary users in fading channels under interference and transmit power constraints. In [3], authors present a power control algorithm for cognitive networks in order to reach high QoS level and mitigate harmful interference at the primary user in shared spectrum areas.

A power control policy in different distributed fading channels is introduced in [4] and concurrently capacity of the cognitive radio in shared spectrum area is investigated. In this case cognitive radio utilizes the license spectrum bands as long as its interference power to the primary user remains below a tolerable level. An adaptive power control policy in perfect channel based on maximizing capacity of cognitive users under constraints of interference and transmit power is introduced in [5]. In this case the Secondary User (SU) is allowed to retransmit in the PU band as long as interference at the PU remains below the nominated tolerable interference.

In all previous works, ergodic capacity as a channel model is considered although it is not desirable in delay sensitive cases. In video and audio wireless communication equipment, high QoS level and minimum data transmit delay are essential characteristics, because of the required speed and data source traffic. To this respect, a reliable wireless channel model with statistical QoS can support real–time services high data rate transmission. Consequently, in varying wireless channel, the QoS metrics such as data rate, delay, and delay-violation probability play essential role in channel modeling. Effective Capacity (EC) is a new approach to model the wireless channel to support data transmission with a diverse statistical QoS.

In this paper our goal is to put emphasis on maximizing the effective capacity of the cognitive radio under the constraints of the interference power and transmit power in spectrum sharing area. In this case the license exempt user desires to reach maximum transmit capacity (bps) under proposed power policies at physical layer.

The rest of this article is organized as follows. In section 2, we propose system and channel models, explanation on effective bandwidth and effective capacity concepts are described. In section 3, the power control policy under average interference and peak transmit power are calculated. Power control policy under peak interference power and average transmit power are analyzed in section 4. In section 5, we present and compare the numerical evaluation of the proposed power control policies. Finally we conclude the paper in section 6.

2 System and Channel Models

We consider a spectrum sharing environment (shown in Figure 1) in which a secondary user is allowed to use license spectrum as long as the introduced interference power to the primary receiver is less than the nominated interference constraint. Let us consider a varying time channel with perfect channel side information at the receiver of the primary user. The received signal at the receiver can be expressed as;

$$y(n) = G(n).s(n) + z(n)$$

Where $y(n)$ is the received signal at the receiver, $G(n)$ the channel power gain between transmitter and receiver, $s(n)$ the transmitted signal by transmitter, $z(n)$

represents the Additive White Gaussian Noise (AWGN) channel and n is time index. We assume $g_0$the channel power gain between secondary transmitters and primary receiver and g_1, channel gain between secondary transmitter and secondary receiver. In this work knowledge of $g_0$is available at the primary receiver and secondary transmitter. The channel information can be sent as feedback from primary receiver to secondary transmitter via different methods [6, 7 and 8].

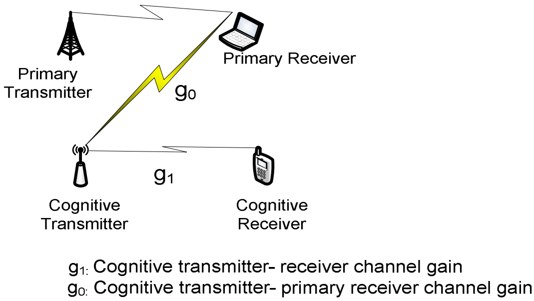

Fig. 1. Shared Spectrum Area

We assume that the channel gain follows Naka gami-m fading [9], and then the probability density function (PDF) of the total channel power gain is given by;

$$f(g) = \frac{1}{\Gamma(m)} g^{m-1} (\frac{m}{\bar{g}})^m \exp\left(-\frac{mg}{\bar{g}}\right), \quad g \geq 0 \tag{1}$$

Where, $\Gamma(.)$ is Gamma function and m denote the Naka gami -m parameter. $\bar{g}$ is average total channel power gain, which is expressed as $\bar{g} = E(g)$. We assume that g_0 and g_1 are independent from each other with their PDFs function. The proposed system model and power control policy at physical layer is shown in figure 2. In this case the QoS constraint block supports the power policy and modulation block at physical layer.

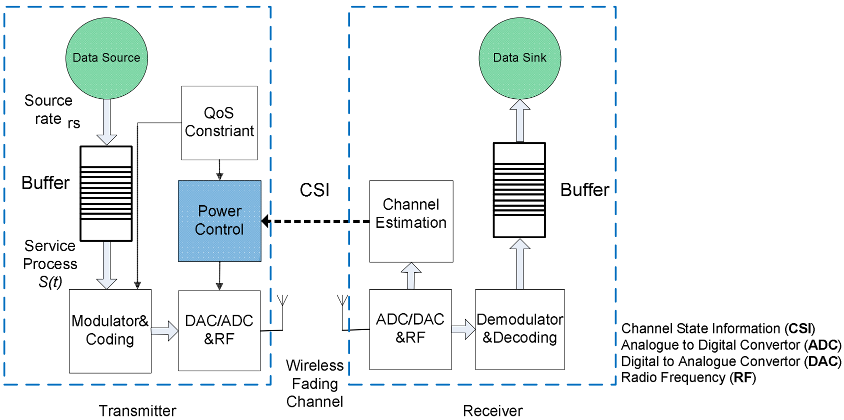

Fig. 2. System architecture (Transmitter and Receiver in proposed system)

2.1 Effective Bandwidth and Effective Capacity

In wireless communication systems, packet switching is expected to handle diverse multimedia traffic. The difference between circuit switching and packet switching is that packet switching requires queuing analysis of the link. Many researchers focused on the statistical QoS using a queuing model in wired links. Moreover the queue model shows that the source traffic and network service are matched by First-In-First-Out (FIFO) buffer. The queue prevents loss of packets during data transmission when the source rate is more than the service rate, at the expense of increasing delay (see figure 2).

The concept of effective bandwidth is proposed to characterize traffic and the utilization of wire line network resources, on the other hand effective bandwidth is the minimum bandwidth required to provide the requested service. In [10], authors defined effective capacity as a dual concept to the effective bandwidth and the quantifying is the maximum arrival rate that a time varying service process can support while satisfying the required QoS specified by the QoS exponent parameter (θ).

The concept of the effective capacity is extended in to wireless channels by Wu and Negi [10] in order to evaluate the capability of a varying wireless channel to support data transmission with diverse statistical quality of service (QoS) guarantees. In this respect the physical layer channel model explicitly characterizes a wireless channel in terms of the link level QoS metrics specified by users, such as data rate, delay and delay violation probability. In [10], effective capacity is modeled by moving physical layer to link layer.

In the rest of this section effective bandwidth and effective capacity functions are represented. By consideration an arrival process $\{A(t), t \geq 0\}$ where $A(t)$ represents the amount of source data (in bits) over the time interval$[0, t)$. Thus the asymptotic log-moment generating functions of a stationary process$A(t)$, defined as;

$$\Lambda(\theta) = \lim_{t \to \infty} \frac{1}{t} log \mathbb{E} e^{\theta A(0,t)}$$

$$a(\theta) = \frac{\Lambda(\theta)}{\theta}$$

$a(\theta)$ is the effective bandwidth function of the arrival process and θ is the decay rate. According to $\Lambda(\theta)$ property (convex), the effective bandwidth function is increasing inθ. As$\theta \to 0$, the function approach to average rate and if $\theta \to \infty$, then $a(\theta)$ function reach peak rate.

Let assume fixed user rate r_s, a delay bound D_{max} and required delay bound violation probability ε then probability of the delay packet when the buffer length is infinite (see Fig.2) can be expressed by:

$$pr(D(\infty) > D_{max}) \leq \varepsilon$$

Here, $D(\infty)$ is the steady state delay experienced by a single flow. On the other hand, the user is specified by the QoS triplet$\{r_s, D_{max}, \varepsilon\}$. Moreover, if Q is defined as the stationary queue length, then θ is defined as the decay rate of the tail distribution of the queue length Q:

$$\lim_{q\to\infty}\frac{\log Pr(Q\geq q)}{q}=-\theta$$

Therefore, for large q (q_{max}), the buffer violation probability corresponds to $\Pr(Q \geq q_{max}) \approx e^{-\theta q_{max}}$.

Consequently the outcomes show that a smaller θ corresponds to a slower decay rate and the system can tolerate an arbitrary long delay or looser QoS guarantees. In contrast larger θ corresponds to more delay constraint. These results provide a link between the buffer and violation probability.

Let $r(t)$ be the instantaneous channel capacity at time t and $S(t)=\int_0^t r(\tau)d\tau$ be sum of the service process then the Gärtner-Ellis limit of $S(t)$ is expressed as;

$$\Lambda(\theta)=\lim_{t\to\infty}\frac{1}{t}log\mathbb{E}e^{\theta S(t)}$$

$\Lambda(\theta)$ is a convex function different for all real θ. Thus, the effective capacity of the service process is depicted by $E_c(\theta)$, where $0<\theta<\infty$ and defined as [11];

$$E_c(\theta)=\frac{-\Lambda(-\theta)}{\theta}=-\lim_{t\to\infty}\frac{1}{\theta t}log\mathbb{E}e^{-\theta\int_0^t r(\tau)d\tau}$$

When the $r(t)$ is uncorrelated, constant during frame duration T and changes independently frame to frame then the effective capacity $E_c(\theta)$ reduced to

$$E_c(\theta)=-\frac{1}{T\theta}\log\left(\mathbb{E}e^{-\theta TR}\right) \quad (2)$$

In this respect it is easy to show that effective capacity specializes to Shannon capacity and delay limited capacity. The throughputs reveal that the effective capacity converges to Shannon ergodic capacity while $\theta\to 0$, means the system can tolerate long delay. Beside, the effective capacity becomes stricter as $\theta\to\infty$, (more delay constraint). Moreover by exploiting different modulation types R becomes Shannon capacity during a frame. In this case the proposed power control scenario adapts frame to frame independently, based on channel state information.

3 Average Interference and Peak Transmit Power

In this section, effective capacity of the cognitive transmitter is maximized in the aforementioned spectrum sharing area subject to average interference (Qav) constraint at the primary user and peak transmit power (P_p) constraint at the cognitive user. We assume the packet service rate at the transmitter satisfies AWGN channel rate. To this end, our objective relies on power control policy for satisfying maximum EC at the cognitive user. Thus by substituting Shannon capacity into (2) and minimizing $\mathbb{E}e^{-\theta R}$, effective capacity of the cognitive transmitter maximizes. The problem can be formulated mathematically, by using Qav and P_p constraints as;

$$\begin{aligned} \text{P1:}\quad & Min\ \ \mathbb{E}\left\{e^{-\theta T f B \log_2\left(1+\frac{g_1 p(g_0,g_1,\theta)}{NB}\right)}\right\} \\ \text{St.}\quad & E\big(g_0 p(g_0,g_1,\theta)\big) \le Qav \\ & p(g_0,g_1,\theta) \le P_p \\ & p \ge 0 \end{aligned} \tag{3}$$

We assume N, B and $Tf = 1$ (NB represent noise power), $E(.)$ denotes the statistical expectation, Tf packet duration and B bandwidth. It is easy to verify that P1 is a convex optimization problem and by applying the standard Karush-Kuhn-Tucker (KKT) optimality conditions [12] the Lagrange function of P1 can be written as;

$$L(p(g_0,g_1,\theta),\lambda,\xi,\zeta) = \mathbb{E}\{e^{-\theta T f B \log_2(1+g_1 p(g_0,g_1,\theta))}\} + \lambda\big(E\big(g_0 p(g_0,g_1,\theta)\big) - Qav\big) + \xi\big(p(g_0,g_1,\theta) - Pp\big) - \zeta p(g_0,g_1,\theta)$$

Where, λ, ξ andζ are Lagrange multipliers. The solution of the above equation is the optimal power control policy which can be expressed as;

$$p(g_0,g_1,\theta) = \begin{cases} 0 & g_0 \ge \frac{g_1}{\lambda'} \\ \left(\left[\frac{\lambda'}{g_1} g_0\right]^{\frac{-1}{\delta+1}} - 1\right)\frac{1}{g_1}, & \frac{g_1}{\lambda'} \ge g_0 \ge \frac{g_1}{\lambda'(g_1 Pp+1)^{\delta+1}} \\ Pp & g_0 \le \frac{g_1}{\lambda'(g_1 Pp+1)^{\delta+1}} \end{cases} \tag{4}$$

Where $\delta = \frac{\theta T f B}{Ln2}$ is normalized QoS exponent and $\lambda' = \frac{\lambda}{\delta}$ is a nonnegative dual variable and if $E\big(g_0 p(g_0,g_1,\theta)\big) \le Qav$ is satisfied with strict inequality, λ' must be zero otherwise λ' can be obtained by satisfying $E\big(g_0 p(g_0,g_1,\theta)\big) = Qav$. Consider when $\rightarrow 0$, (4) follows the power allocation in [3] which maximizes ergodic capacity, it means that the system can tolerate an arbitrary long delay. Furthermore the results reveal that the power policy is function of channel gains and QoS exponent or queue delay. Moreover, due to the g_0 and g_1 states the effective capacity at the cognitive user can be achieved by substituting (4) and channel gain PDF functions (e^{-g_0} and e^{-g_1} achieved from (1)) into (2). Consequently, the effective capacity at the license exempt user is expressed as;

$$E_c(\theta) = -\frac{1}{\theta}\log \int_{g_1}\int_{g_0} \left(\left(\frac{\lambda'}{g_1} g_0\right)^{\frac{\delta}{\delta+1}} + (1+g_1 P_P)^{-\delta}\right) f(g_0)\, f(g_1) dg_0 dg_1 \tag{5}$$

4 Peak Interference and Average Transmit Power

In this section, we concern on second scenario in which peak interference power (Q_m) and average transmit power (P_{av}) constraint are use to obtain optimal power control policy. We assume the cognitive radio effective capacity under the constraints approach to maximum level. As we mentioned in the previous section the solution of the following formulated problem, is the optimal power policy. The maximizing effective capacity subject to maximum interference power and average transmit power limitation is written as;

$$\text{P2:} \quad Min \ \mathbb{E}\left\{e^{-\theta T f B \log_2\left(1+\frac{g_1 p(g_0, g_1, \theta)}{NB}\right)}\right\} \tag{6}$$
$$\text{St.} \quad g_0 p(g_0, g_1, \theta) \le Q_m$$
$$E(p(g_0, g_1, \theta)) \le Pav$$
$$p \ge 0$$

P2 is a convex optimization problem and by applying the standard Karush-Kuhn-Tucker (KKT) optimality conditions [12] the Lagrange function of P2 can be structured as;

$$L(p(g_0, g_1, \theta), \lambda, \xi, \zeta) = \mathbb{E}\{e^{-\theta T f B \log_2(1+g_1 p(g_0, g_1, \theta))}\} + \lambda\big(E\big(p(g_0, g_1, \theta)\big) - Pav\big) + \xi(g_0 p(g_0, g_1, \theta) - Q_m) - \zeta p(g_0, g_1, \theta)$$

Where λ, ξ and ζ are Lagrange multipliers. The optimal power control solution subject to the aforementioned constraints in (6) can be shown as;

$$\boldsymbol{P} = \begin{cases} 0 & g_1 \le \frac{\lambda}{\delta} \\ \left[\left(\frac{\delta g_1}{\lambda}\right)^{\frac{1}{1+\delta}} - 1\right]\frac{1}{g_1} & g_1 > \frac{\lambda}{\delta},\ g_0 \le \frac{Q_m}{\left[\left(\frac{\delta g_1}{\lambda}\right)^{\frac{1}{1+\delta}} - 1\right]\frac{1}{g_1}} \\ \frac{Q_m}{g_0} & g_1 > \frac{\lambda}{\delta},\quad g_0 > \frac{Q_m}{\left[\left(\frac{\delta g_1}{\lambda}\right)^{\frac{1}{1+\delta}} - 1\right]\frac{1}{g_1}} \end{cases} \tag{7}$$

As, $\delta \to 0$ equation (7) approximates (5) in [3]. It means that when QoS exponent reaches zero the power control policy follows the optimal power allocation strategy to achieve maximum ergodic capacity in [3]. Thus λ is a nonnegative dual variable and if $E(p(g_0, g_1, \theta)) \le Pav$ is satisfied with strict inequality, λ must be zero otherwise λ can be obtained by satisfying $E\big(p(g_0, g_1, \theta)\big) = Pav$. Furthermore, depending on $g_0$and g_1 values, the power policy follows (7). It should concern that channel gains and QoS exponent or delay affect power value in each data frame. To this end, by replacing (7) and channel PDF functions (e^{-g_0} and e^{-g_1}) into (1), the effective capacity under this power policy can be rewritten as;

$$E_c(\theta) = -\frac{1}{\theta}\log \int_{g_1}\int_{g_0}\left(\left(\frac{\delta g_1}{\lambda}\right)^{\frac{-\delta}{1+\delta}} + (1 + g_1\frac{Q_m}{g_0})^{-\delta}\right) f(g_0)\, f(g_1) dg_0 dg_1 \tag{8}$$

5 Numerical Results

In this section we present the mathematical results of the discussed power policy in earlier sections. Let us assume the probability density function of the channels obeys equation (1) with m=1 and$T_f.B = 1$.

The simulation results of the effective capacity of the cognitive user subject to the interference and transmit power constraints at the primary and secondary users are shown in the following figures (3, 4).

Figure 3 demonstrates that effective capacity under peak transmits power and average interference power has less derivation as long as the QoS exponent reaches

0.1. The results achieved under Qav=10dB. It is observed that high effective capacity level occurs while peak transmit power of the cognitive radio is rising and then the system transmits more bits over the wireless channel. Moreover the simulation results reveal that the maximum effective capacity reach 3.7 under$Pp = 15$dB, 20dB and $\theta = 0.01$. It means that the system can tolerate arbitrary delay and effective capacity approach to Shannon capacity while $\theta \to 0$. Furthermore by increasingθ, the QoS of the system becomes strict. In spite of increasing peak power (more than 15dB) the effective capacity remains constant because of the average interference constraint on the power control policy. It is observed that when QoS exponent is small (less than 0.1) the effective capacity can be satisfied regarding acceptable range of effective capacity.

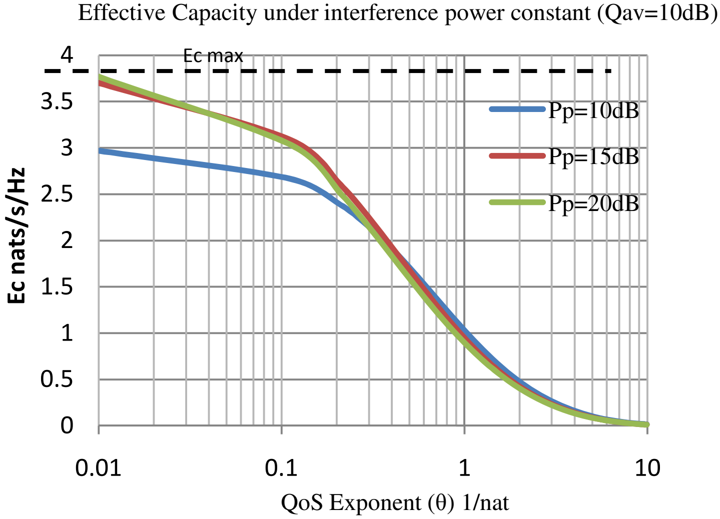

Fig. 3. Effective Capacity (EC) versus QoS Exponent (θ) under average interference power and cognitive radio transmit power

Figure 4 depicts that the effective capacity versus QoS exponent under peak interference power and average cognitive radio transmit power constraints. The results reveal that the effective capacity is fixed as long as QoS exponent reach 0.2. Moreover, it is observed that QM affects the effective capacity, directly. Explicitly, QM limits the performance of the system.

Consequently, the results show that cognitive radio increases its power to achieve more effective capacity, under maximum interference power, mean while the tolerable QoS exponent (θ) becomes small. For instance, when QM =3 dB, the effective capacity of the system satisfies as long as θ reach 1.0. While QM =10 dB, satisfied θ reach 0.2.

The curves demonstrate that effective capacity versus QoS exponent in terms of the interference power and average transmit power is more stable than previous power policy, regarding the variation of QoS exponent. It can be noted that the system can tolerates more delay under aforementioned constraints.

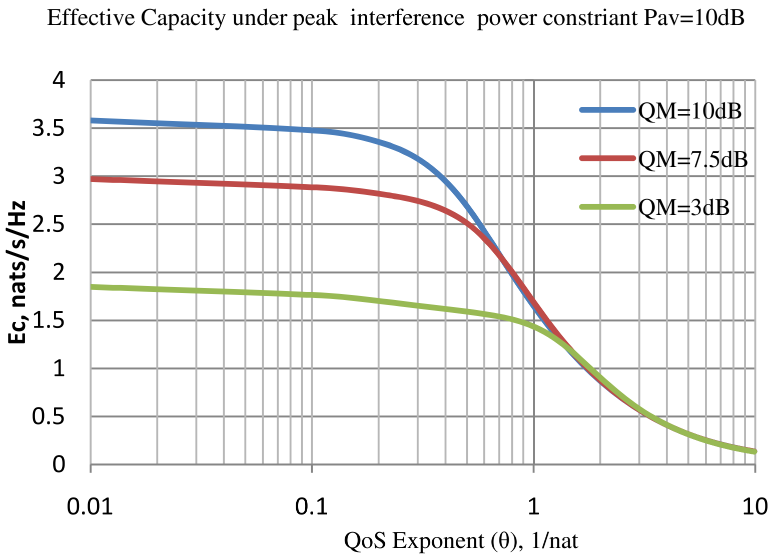

Fig. 4. Effective Capacity (EC) versus QoS Exponent (θ) under average transmit power and peak interference power in spectrum sharing area

Figure 5 reveals the effective capacity under average interference power constraint and peak transmits power constant. The curves achieved under Pp=15dB while average interference power (Qav) obtains two value.

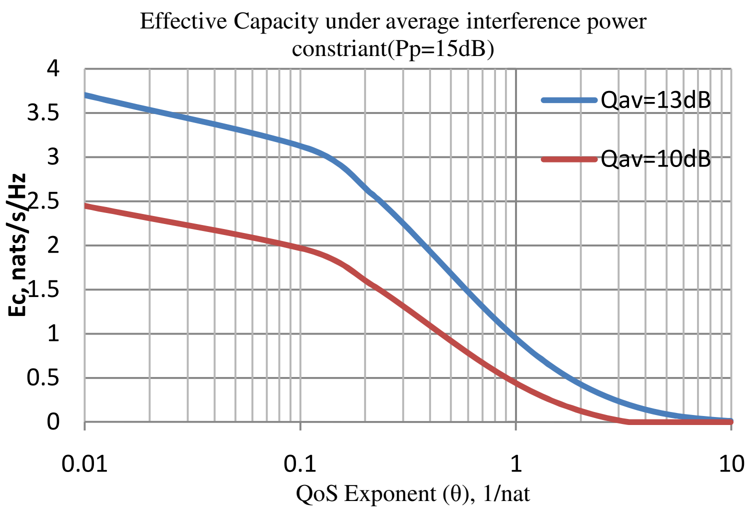

Fig. 5. Effective Capacity (EC) versus QoS Exponent (θ) under average interference power

It is observed that Qav directly affected the effective capacity value. It means cognitive radio is using more power to enhance its QoS level. Moreover the curves show that the effective capacity range is acceptable while QoS exponent changes from 0.01 to 0.1. The outcomes reveal that the system can tolerate delay as long as θreachs 0.1. Concurrently, the QoS of the system becomes strict by increasing θ (more than 0.1).

6 Conclusions

In this paper we investigated and proposed a power control policy in spectrum sharing area under specific constraints. Simultaneously, the cognitive users are allowed to use licensed spectrum without harming the primary user. In this case, the proposed power control policy and QoS constraint drive the data queue at the link layer. The concept of maximizing effective capacity which is represented by the QoS exponent was our main goal.

The objectives relied on the secondary user effective capacity optimization subject to the constraints of the interference power and transmit power. The proposed power policies performances showed that the power control under peak interference power and average power constraints can be considered due to QoS level and delay constraints. The performance evaluation confirmed our proposed power control achievements. To this end, the power control policies could be exploited in wireless channel models based on using queue at the link layer and applying effective capacity over wireless channel.

In the future we would like to increase the number of cognitive users and employ a new cooperative power control policy on the secondary users for optimizing capacity with respect to interference and power constraints.

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