Spectral-Energy Efficiency Tradeoff in Cognitive Radio Networks with Peak Interference Power Constraints

(Invited Paper)

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***Abstract*— Cognitive Radio (CR) is considered as one of the prominent techniques to improve the spectrum utilization by opportunistically sharing the radio spectrum resources with licensed users. This paper concentrates on characterizing the spectral-energy efficiency tradeoff in low and high signal-to-noise ratio (SNR) regimes for interference-tolerant CR networks under peak interference power constraints and in different fading environments. The analysis has been conducted under an assumption that perfect channel state information (CSI) of both primary and secondary receivers is available at the secondary transmitter. Our analysis proves that, in the low SNR regime, the minimum energy per bit required for reliable transmission is characterized by the supremum of the CR fading channel.**

I. Introduction

The increase in multimedia load and data usage everyday puts pressure on the wireless service provider to offer faster and more efficient wireless access. It follows that there is an increasing demand for new spectrum bands. The radio spectrum, however, is very scarce and most of the available spectrums have already been allocated to various wireless communication systems such as mobile cellular systems, Digital Video Broadcasting (DVB), Wireless Local Area Networks (WLANS), etc. On the other hand, the Federal Communications Commission (FCC) has reported that at while some spectrum bands are heavily utilized by licensed systems, most parts of the spectrum are either partly occupied or mostly unoccupied for a long period of time [1]. This was the motivation behind to introduce the concept of CR as a solution to the congested spectrum problem [2]–[4].

CR is an innovative radio device that aims to utilize the spectrum more efficiently by exploiting opportunistically underutilized licensed spectrum. CR networks can be divided into two categories, namely interference-free (spectrum overlay) and interference-tolerant (spectrum underlay). In interference-free CR systems, CR (secondary) users are allowed to access spectrum resources only when primary users do not use them. Whereas in interference-tolerant systems, secondary users can share the spectrum resource with primary users while keeping the interference to primary users below a threshold.

Most of the previous performance studies for interference-tolerant CR networks have mainly focused on capacity analysis [5]–[11]. The capacity of CR networks in AWGN channels was derived in [5] under an average received power constraint. In [6], the capacity of CR channels was analyzed for different fading distributions. The authors of [7] derived the optimal power allocation policies for CR users subject to joint transmit and interference power constraints. In [8], ergodic and outage capacities of CR networks were evaluated under both peak and average interference power constraints. In [9], the system-level capacity was studied for multiuser CR systems under average interference power constraints. In [10], both the link- and system-level capacities of cooperative hybrid CR networks were studied under average interference power constraints.

Energy-efficient communications have recently attracted more and more attention in research communities [12]. Reducing energy consumption is very important in order to minimize carbon footprint from wireless networks on the environment. It is also important because mobile terminals have batteries with limited energy supply. Energy efficiency can be measured as the required energy to send one bit reliably over a communication channel. Two analytical methods to analyze the spectral-energy efficiency tradeoff were proposed in [13] and [14] for low SNR regime (power-limited) and high SNR regime (bandwidth-limited), respectively. These methods have been used to analyze the spectral-energy efficiency tradeoff in different network scenarios. Using the low-SNR method, the interplay of the energy and spectral efficiencies was studied for single-user MIMO channels [15], single-user relay channels [16]–[18], and multi-users scenarios [19]. The authors of [20], [21] used the high-SNR method to analyze the energy efficiency in multi-antenna channels. To the best of our knowledge, no existing work has investigated the spectral-energy efficiency tradeoff in interference-tolerant CR networks. This paper is to fill the gap, i.e., we will characterize the spectral-energy efficiency tradeoff in CR networks in low and high SNR regimes under peak interference power constraints.

The rest of this paper is organized as follows. Section II describes the system model. In Section III, the relationship between the energy efficiency and spectral efficiency is analyzed for a fading channel in low and high SNR regimes. Section IV presents simulation results with detailed analysis. Finally, Section V concludes the paper.

II. System Model

The system model is shown in Fig 1. It consists of an interference tolerant CR network that shares a spectrum with a single primary transmitter-receiver pair. A point-to-point flat fading channel that is corrupted by additive white Gaussian noise (AWGN) is assumed. All nodes in this model are assumed to be equipped with a single antenna. We denote h_1 and h_2 as the complex-valued channel gains from the secondary transmitter (SU_t) to the secondary receiver (SU_r) and the primary receiver (PU_r), respectively. The average powers are random variables with an expected value of unity, i.e., $E[|h_1|^2]$= $E[|h_2|^2]$ =1, and they are mutually independent. We consider the case when the channel fading level is known to both primary and secondary receivers. The secondary transmitters are assumed to have perfect knowledge of the instantaneous CSI on h_1 and h_2 as well as the statistics of the both channel variations. The feedback control channel from primary to secondary networks is beyond the scope of this paper. It is further assumed that the interference from the primary transmitter to the secondary receiver can be considered as Gaussian noise [6], [22]. There are two types of power constraints that the secondary transmitter has to take into account. The first constraint is the maximum average transmit power that the SU_t can emit. The second constraint is the allowable received peak interference power that the primary network can accept.

III. Spectral-Energy Efficiency Tradeoff in CR Networks

A. AWGN Channel

Let us first analyze the required energy per bit in an AWGN channel where the instantaneous signal powers, $g_1 = |h_1|^2$ and $g_2 = |h_2|^2$, are equal to 1. We denote P_s as the average secondary transmit power, B as the system bandwidth, and N_0 as the noise spectral density. Since the interference from the primary network is considered as Gaussian noise, the secondary transmitted SNR ($\bar{\gamma}$), which is equal to the received SNR in the AWGN channel, is then equal to $\frac{P_s}{BN_0}$. The spectral efficiency, in bit/s/Hz, can be simply obtained by

$$C = \begin{cases} \log_2(1+\bar{\gamma}) & \forall \bar{\gamma} \leq Q_{\text{pk}} \\ \log_2(1+Q_{\text{pk}}) & \text{otherwise} \end{cases} \quad (1)$$

where Q_{pk} is the peak received interference power (normalized to the background noise power) that the primary receiver can tolerate.

B. Fading Channels with Peak Received-Power Constraint

In this section, we consider a fading channel under a peak-power constraint on the primary receiver. The spectral efficiency in this case is given by [22]

$$C = \max_{\gamma_s(g_1,g_2)\geq 0} E[\log_2(1+g_1\gamma_s(g_1,g_2)] \quad (2)$$

$$\text{s.t.} \quad E[\gamma_s(g_1,g_2)] \leq \bar{\gamma} \quad (3)$$

$$g_2\gamma_s(g_1,g_2) \leq Q_{\text{pk}} \quad (4)$$

where $\gamma_s(g_1,g_2)$ is the optimum value of the transmitted SNR such that the constraints (3) and (4) can be met. Adopting a similar approach that been used in [22], the optimization problem (2), (3) and (4) can be solved using Lagrangian optimization approach. Thus,

$$\begin{aligned} L(\gamma,\lambda,\nu) = E[\log_2(1+g_1\gamma_s(g_1,g_2))] \\ -\lambda(E[\gamma_s(g_1,g_2))] - \bar{\gamma}) \\ -\nu(g_2\gamma_s(g_1,g_2) - Q_{\text{pk}}) \end{aligned} \quad (5)$$

where λ and ν are the the Lagrange multiplier factors associated with constraints (3) and (4), respectively. The expectation $E[.]$ is with respect to the two random variables g_1 and g_2. It is necessary that the optimization objective and its constraints must fulfil the Karush-Kuhn-Tucker (KKT) conditions for optimality. Hence, the optimal value of power allocation, $\gamma_s^*(g_1,g_2)$, can be found by differentiate the Lagrange dual function with respect to P and set it to zero, i.e., $\frac{dL(\gamma_s,\lambda,\nu)}{d\gamma} = 0$. The optimum power allocation for this case has been found to be [22]

$$\gamma_s^*(g_1,g_2) = \min\left\{\left(\frac{1}{\gamma_0} - \frac{1}{g_1}\right)^+, \frac{Q_{\text{pk}}}{g_2}\right\} \quad (6)$$

where $(x)^+$ is the $\max\{0,x\}$ function and γ_0 is the water-filling cutoff value which can be found from the constraint (3). Numerical optimization is required to get the optimum value of γ_0. Fig. 2 shows different value of the cutoff γ_0 value versus SNR under different peak interference constraints, Q_{pk}.

It can be seen from (6) that the power control has three different regions based on the two channel states of SU_t-PU_r and SU_t-SU_r. In the first region, the cognitive channel can not be used as long as the channel state of SU_t-SU_r is below the cutoff value, $g_1 \leq \gamma_0$. In the second regime, the classical water filling algorithm can be adopted if the channel states of SU_t-SU_r is greater than the cutoff value, $g_1 > \gamma_0$ and the power allocation based on water is below $\frac{Q_{pk}}{g_2}$, i.e., $\left(\frac{1}{\gamma_0} - \frac{1}{g_1}\right) \leq \frac{Q_{pk}}{g_2}$. Finally, for the third region, which corresponding to $g_1 > \gamma_0$ and $\left(\frac{1}{\gamma_0} - \frac{1}{g_1}\right) > \frac{Q_{pk}}{g_2}$ the power allocation is equal to $\frac{Q_{\text{pk}}}{g_2}$.

1) Spectral Efficiency vs. Bit Energy in the Low SNR regime: The spectral-energy efficiency tradeoff is analyzed herein for a CR channel in low SNR regime, i.e., low power and wideband regimes. It has been shown in [13] that the spectral-efficiency (C) can be approximated as an affine function with respect to $\frac{E_b}{N_0}$. i.e.,

$$\text{C}\left(\frac{E_b}{N_0}\right) \approx \frac{S_0}{3}\left(\left.\frac{E_b}{N_0}\right|_{\text{dB}} - \left.\frac{E_b}{N_0}_{\text{min}}\right|_{\text{dB}}\right) \quad (7)$$

where $\frac{E_b}{N_0}_{\text{min}}$ is the minimum energy per bit (normalized to the background noise spectral level) required for transmitting information reliably over a channel which can be expressed as a function of SNR [13]

$$\frac{E_b}{N_0}_{\min} = \lim_{\text{SNR}\to 0} \frac{\text{SNR}}{C(\text{SNR})} \quad (8)$$

$$= \frac{\log 2}{\dot{C}(0)} \quad (9)$$

where $\dot{C(0)}$ is the first-order derivatives of $C(\text{SNR})$ at SNR=0. The purpose here of using different notations for spectral efficiency to distinguish between the spectral efficiency as a function of transmit signal-to-noise ration, i.e., $C(\text{SNR})$, and as a function of $\frac{E_b}{N_0}$, i.e., $\text{C}(\frac{E_b}{N_0})$, respectively. The wideband slop S_0 of the spectral efficiency at $\frac{E_b}{N_0}_{\min}$ is measured in b/s/Hz/(3dB) and expressed by [13]

$$S_0 = \lim_{\frac{E_b}{N_0}\downarrow\frac{E_b}{N_0}_{\min}} \frac{3\text{C}(\frac{E_b}{N_0})}{10\log_{10}\frac{E_b}{N_0} - 10\log_{10}\frac{E_b}{N_0}_{\min}}. \quad (10)$$

It has been shown in [14] that in the case of no power control, i.e., no channel state information at the transmitter, the minimum bit energy and the wideband slop can be expressed as $\frac{E_b}{N_0}_{\min} = \frac{\log 2}{E[|h_d|^2]}$ and $S_0 = \frac{2}{\kappa(|h_d|)}$, respectively. Where $\kappa(|x|) = \frac{E[|x|^4]}{E[|x|^2]^2}$ is the $Kurtosis$ of a real random variable x. In cognitive radio network, however, power control in is essential to avoids a harmful interference to the primary users. Unlike the primary network where only the CSI of the primary receiver is required at the primary transmitter to allocate the power, both secondary and primary receivers CSI are needed as inputs for the power allocation algorithm at the secondary transmitter.

$Theorem$ 1: Under peak-power constraint, the minimum energy required for reliable information over the cognitive channel is

$$\frac{\log 2}{g_{1(\max)}} \quad (11)$$

where $g_{1(\max)}$ is the supremum of a random variable g_1, $P(g_1 \le g_{1(\max)}) = 1$, that represents the fading states of the cognitive channel.

$Proof$: If we expand the expection in (3) as an integral in (15). We can notice from (6) and (15) that the SNR vanishes when γ_0 approaches $g_{1(\max)}$. Furthermore, Eq. (16) can be re-written as (17), and (18) can be obtained by applying L'Hpital's Rule to (17) followed by Leibniz Integral Rule. The term of (19) is obtain after straightforward applying $\gamma_0 \to g_{1(\max)}$.

Therefore, the minimum energy is characterized by the supermum of random variable $g_{1(\max)}$. In AWGN channel, the $\frac{E_b}{N_0}_{\min}$, thus, equals to -1.59 dB. While the wideband slop S_0 is 2 as long as the SNR is below or equal to Q_{pk} and zero otherwise. Whereas in Rayleigh fading channels, the fading distribution is unbounded, i.e., $g_{1(\max)} = \infty$. In this case, Eq. (19) becomes $\frac{E_b}{N_0}_{\min} = 0\ (-\infty \text{ dB})$ and it is easy to see that the S_0 is equal to 0 in this case. It can be noted that the minimum bit energy obtained in cognitive channel to achieve reliable communication is the same as that achieved by Shannon capacity with optimum power allocation.

2) Spectral Efficiency vs. Bit Energy in the High SNR regime: In the high SNR regime (i.e. $\text{C} \to \infty$) the required $\frac{E_b}{N_0}$ to obtain a specific spectral efficiency can be characterized as [14]

$$\frac{E_b}{N_0}(\text{C})\bigg|_{\text{dB}} \approx \frac{\text{C}}{S_\infty} 10\log_{10} 2 - 10\log(\text{C}) + \frac{E_b}{N_0}_{\text{penalty}} 10\log_{10} 2 \quad (12)$$

where S_∞ is the slop of the spectral efficiency in the high SNR regime in bps/Hz/(3 dB)

$$S_\infty = \lim_{\text{SNR}\to\infty} \frac{C(\text{SNR})}{\log_2(\text{SNR})} \quad (13)$$

and $\frac{E_b}{N_0}_{\text{penalty}}$ is horizontal penalty in the high SNR regime with respect to reference unfaded channel [14], i.e.,

$$\frac{E_b}{N_0}_{\text{penalty}} = \lim_{\text{SNR}\to\infty} \left(\log_2(\text{SNR}) - \frac{C(\text{SNR}}{S_\infty}\right). \quad (14)$$

Now, let us assume that the power allocation resides in the second region, i.e., $Q_{pk} < g_2\gamma_s^*(g_1, g_2)$, where a classical water-filling algorithm can be used. It has been shown in [14] that the spectral efficiency as function to $\frac{E_b}{N_0}$ for constant transmitted power is the same for the case without optimal power allocation because the water-filling has a minor impact on the instantaneous transmitted power. Therefore, the slop $S_\infty = 1$ for any fading distribution and $\frac{E_b}{N_0}_{\text{penalty}} = -E[\log_2(|h_1|^2)]$ [14]. If, however, the $Q_{pk} \le g_2\gamma_s^*(g_1, g_2)$, then the $S_\infty = 0$ and $\frac{E_b}{N_0}_{\text{penalty}} = \infty$.

IV. Simulation result and Discussion

In this section, some numerical results of the energy-spectrum efficiency tradeoff is presented for the CR channel in low and high SNR regime. Rayleigh, Rician and AWGN fading channels have been chosen in this analysis. In the simulation, the Rician K factor, K=5, is chosen for Rician fading channel.

Fig. 3 shows the energy-spectrum efficiency tradeoff in the low SNR regime for a Rayleigh fading channel where g_1 and g_2 have an exponential density (i.e. $e^{-x},\ \forall x > 0$). As it is shown, all curves approaches the same minimum bit energy $\frac{E_b}{N_0}_{\min} = -\infty$ dB regardless to the value of Q_{pk}. We also can notice that the required energy is higher as the Q_{pk} decreases. Without peak interference constraint, i.e., $Q_{\text{pk}} = \infty$, the curve approach the one of Rayleigh fading with the traditional water-filling power allocation.

Fig. 4 compares the required bit energy in the cognitive channel under Rayleigh and AWGN channel for various fading distribution of g_2 with $Q_{\text{pk}} = -5$ dB. As clearly shown, the minimum bit energy depends only on the fading statistics of the cognitive channel regardless to the distribution of the fading between the secondary transmitter and primary receiver and this verify $theorem$ 1. We also can notice that the required energy is lower when the channel between secondary transmitter and primary receiver is a Rayleigh fading channel and it higher when the channel is AWGN due to additional gain in the fading channel of SU_t-PU_r in case of a Rayleigh fading channel.

$$\bar{\gamma} = \int_{\gamma_0}^{g_{1(\max)}} \left(\int_0^{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}} \left(\frac{1}{\gamma_0} - \frac{1}{g_1}\right) + \int_{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}}^{\infty} \frac{Q_{\rm pk}}{g_2} \right) f(g_1) f(g_2) dg_1 dg_2 \tag{15}$$

$$\left(\frac{E_b}{N_0}\right)_{\min} = \lim_{\rm SNR \to 0} \frac{\rm SNR}{C(\rm SNR)} \tag{16}$$

$$= \lim_{\gamma_0 \to g_{1(\max)}} \frac{\int_{\gamma_0}^{g_{1(\max)}} \left(\int_0^{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}} \left(\frac{1}{\gamma_0} - \frac{1}{g_1}\right) + \int_{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}}^{\infty} \frac{Q_{\rm pk}}{g_2} \right) f(g_1) f(g_2) dg_1 dg_2}{- \int_0^{g_{1(\max)}} \left(\int_0^{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}} (\log_2(\gamma_0) - \log_2(g_1)) + \int_{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}}^{\infty} \log_2(1 + \frac{g_1}{g_2} Q_{\rm pk}) \right) f(g_1) f(g_2) dg_1 dg_2} \tag{17}$$

$$= \lim_{\gamma_0 \to g_{1(\max)}} \frac{-\left(\frac{1}{\gamma_0^2}\right) \int_{\gamma_0}^{g_{1(\max)}} \int_0^{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}} f(g_1) f(g_2) dg_1 dg_2}{-\frac{1}{\gamma_0 \log 2} \int_{\gamma_0}^{g_{1(\max)}} \int_0^{\frac{Q_{\rm pk}}{\frac{1}{\gamma_0}-\frac{1}{g_1}}} f(g_1) f(g_2) dg_1 dg_2} \tag{18}$$

$$= \frac{\log 2}{g_{1(\max)}}. \tag{19}$$

Fig. 5 presents the spectral-energy efficiency tradeoff in high SNR regime for Rayleigh fading channel. As we can see, the curves behaves as a case of single direct user when the SNR $\ll Q_{\rm pk}$. In this case the relationship between the energy efficiency and spectral efficiency can be approximated to the following [14]

$$\left(\frac{E_b}{N_0}\right)\Bigg|_{\rm dB} \approx \mathrm{C} \times 10 \log_{10} 2 - 10 \log(\mathrm{C}) + 2.5067.$$

V. Conclusions

In this paper, we have studied the energy efficiency in interference-tolerant CR networks under peak interference power constraints for different types of fading channels. The bit energy-spectral efficiency tradeoff has been investigated in both low and high SNR regimes, under optimal power allocation. The simulation results have verified our theoretical derivations. Our future work will focus on analyzing the spectral-energy efficiency tradeoff of CR systems that consist of multiple primary and secondary users.

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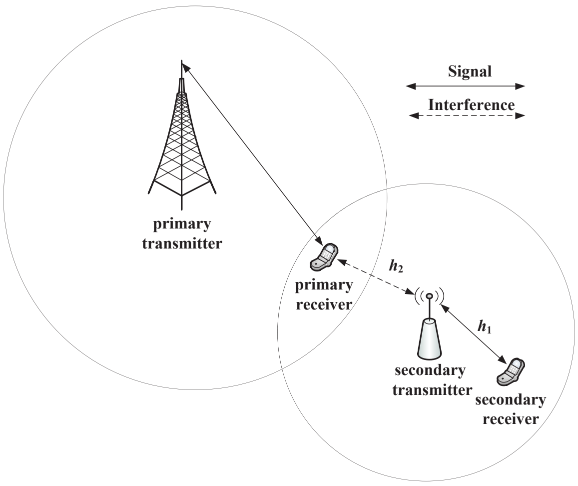

Fig. 1. System model.

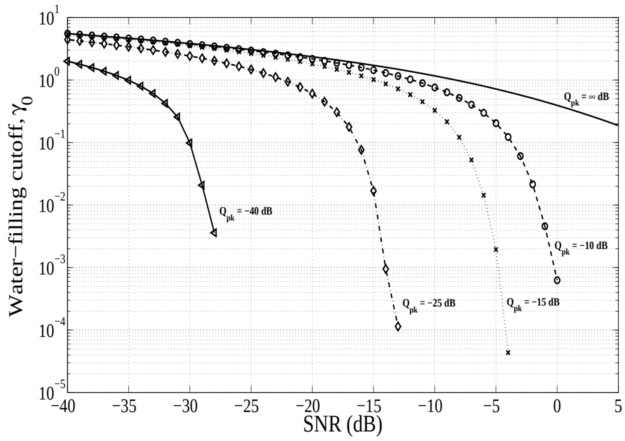

Fig. 2. Cut off values γ_0 versus SNR with optimum power allocation.

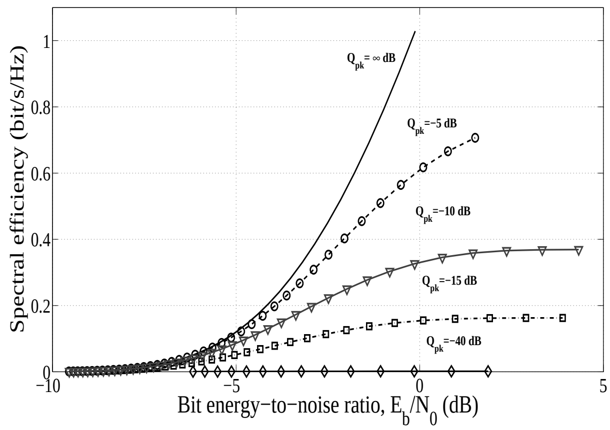

Fig. 3. Spectral efficiency vs. $\frac{E_b}{N_0}$ in low SNR regime.

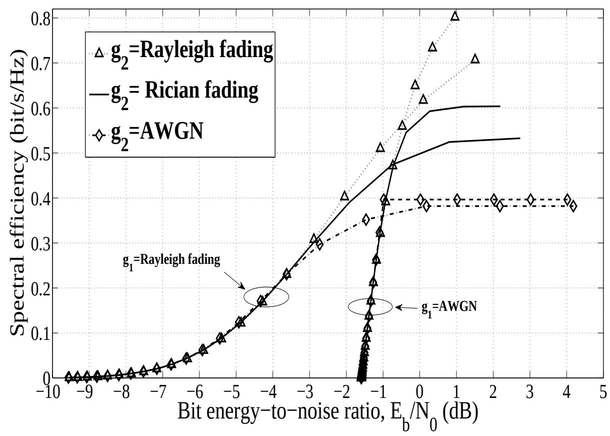

Fig. 4. Spectral efficiency vs. $\frac{E_b}{N_0}$ for different fading distributions of g_2.

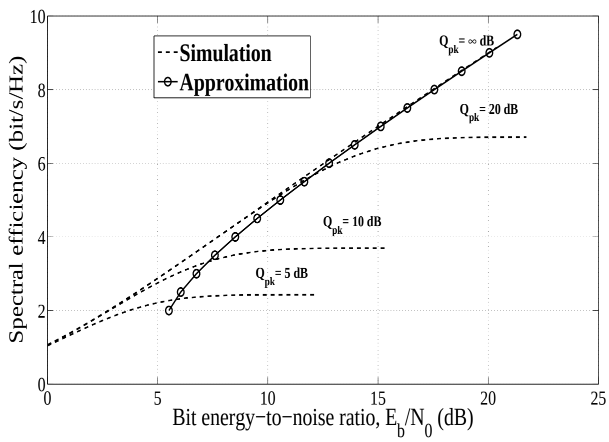

Fig. 5. Spectral efficiency vs. $\frac{E_b}{N_0}$ in high SNR regime.