Theoretical Analysis of Power Saving for Cognitive Radio Systems with Arbitrary Input Distributions

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***Abstract*—In this paper, an optimal power allocation scheme is derived in cognitive radio systems under the condition of finite symbol alphabet input as used in practical communication systems. The proposed scheme is shown to save transmit power compared to its conventional counterpart, which assumes Gaussian inputs. Numerical results reveal that, for distances between the SU transmitter and the PU receiver ranging between 50m to 100m, the transmit power saving with the proposed algorithm is in the range of $13-90\%$ depending on the modulation scheme (i.e., M-QAM) used. Furthermore, a theoretical framework is established in this paper for the derivation of the average optimal power allocation and estimation of power saving. Our theoretical analysis is later verified by simulations and proved to be accurate.**

***Index Terms*—Cognitive Radio, OFDM, Finite Symbol Alphabet, MMSE, Mutual Information.**

I. Introduction

In Cognitive Radio (CR) systems [1], [2], power allocation aims to dynamically control the transmit power on each subcarrier of the SU, in order to reduce the mutual interference. Different power allocation algorithms have been proposed in the literature [3], [4] assuming the Gaussian input to maximize the SU data rate for a given interference threshold value. However, the Gaussian input is not a valid assumption, rather, the Finite Symbol Alphabet (FSA) input is a better model for practical systems, which may significantly depart from the Gaussian assumption. To approximate the difference between Gaussian and FSA input distributions, SNR gap model has been proposed [5], but this approach is not valid for higher SNR values due to large difference gap. In [6], [7], authors derived optimal power allocation using the FSA input in a non-cognitive scenario, whereas in an interference limited system, the same power allocation algorithms cannot be applied due to mutual interference, which degrades the performance of both PU and SU networks. To the best of our knowledge, no work has been done to derive and evaluate optimal power with arbitrary input distributions in CR systems. Therefore, in [8] we derived an optimal power scheme for the FSA input by capitalizing on the relationship between Mutual Information (MI) and Minimum Mean Square Error (MMSE) [9]. We showed that if the conventionally optimized power under the Gaussian input assumption is used for FSA transmission, there is a wastage of transmit power. Whereas, our proposed optimal power allocation scheme leads to a significant power saving. This further motivates us to evaluate theoretically the proposed power allocation scheme in an attempt to gain deeper insights into its power saving capability. Our analysis is later verified by simulations and shown to be accurate.

II. System Model

We consider a system model presented in [8], [3]. It is assumed that the SU employs OFDM modulation for transmission, where the available bandwidth is divided into N subcarriers and frequency spacing between two adjacent subcarriers is Δf. We consider the co-existence of a PU and a SU in a frequency domain where the user data are mapped to consecutive subcarriers.

In the CR system, the transmit power and achievable data rate of the SU are limited by the interference threshold imposed by the PU. Therefore, we propose to calculate an optimal power with the FSA input based on the convex optimization problem. The relationship between MI and MMSE is the key to solve the optimum power allocation problem and is given by [9]

$$I(snr, S) = \int_0^{snr} mmse(\gamma, S) d(\gamma, S), \tag{1}$$

where $I(.)$ represents MI, S denotes an arbitrary input distribution, (e.g., M-QAM or Gaussian) and the MMSE expression with respect to SNR can be found in [6].

In an interweave spectrum sharing scheme, two types of interference, i.e., the one from SU into the PU and vice versa, are introduced to the system. Our objective is to protect the PU from an unacceptable interference, therefore, we will only consider interference introduced by the SU into the PU band [3].

$$J_n(\ell_n, p_n) = p_n T_s \int_{(\ell_n - \frac{1}{2})\Delta f}^{(\ell_n + \frac{1}{2})\Delta f} \left(\frac{\sin \pi f T_s}{\pi f T_s} \right)^2 df, \tag{2}$$

where $J_n(.)$ is the interference introduced by the nth subcarrier of the SU into the PU, T_s is the symbol duration, Δf is the frequency spacing between two adjacent subcarriers and ℓ_n represents the spectral distance between the nth subcarrier of the SU and the PU.

III. Optimal Power Allocation Policy

The objective is to calculate an optimal power with the FSA input that maximizes the MI of the SU, provided that the interference introduced into the PUs' band does not exceed a certain level. This problem can be defined as an optimization problem as follows

$$\max_{p_n} \sum_{n=1}^{N} I(p_n g_n, S), \tag{3}$$

subject to

$$\sum_{n=1}^{N} J_n(\ell_n, p_n) = \frac{\tau_{th}}{PL}, \;\; and \;\; p_n \geq 0 \quad n = 1, 2, \cdots, N, \tag{4}$$

where N, τ_{th}, p_n and g_n represents total number of available subcarriers, interference threshold prescribed by the PU, SU transmit power at the n_{th} subcarrier, and channel gain between the SU transmitter and the SU receiver of the n_{th} subcarrier, respectively. We remove S from equations in the rest of the paper, whenever no ambiguity arises. In Eq. (4), PL is the path loss. We consider a simplified PL model, i.e., $Q(\frac{r_0}{r})$ [10] for our simulations and analysis, where Q, r_0 and r is constant, reference distance and the distance between the SU transmitter and the PU receiver in meters, respectively.

Theorem 1: Optimal power with an arbitrary input distribution that maximizes the SU data rate is as follows

$$p_n^\star = \begin{cases} \dfrac{1}{g_n} \text{ mmse}^{-1}\left(\dfrac{\lambda k_n}{g_n}\right) & \text{if } \frac{g_n}{k_n} > \lambda, \\ 0 & \text{if } \frac{g_n}{k_n} \leq \lambda, \end{cases} \tag{5}$$

where $k_n = \frac{\partial J_n}{\partial p_n^\star}$ and λ is the Lagrange multiplier which can be calculated using numerical methods (such as bisection, secant, or Newton) for solving the following equation

$$\sum_{n=1}^{(N, \frac{g_n}{k_n} > \lambda)} \frac{1}{g_n} \text{ mmse}^{-1}\left(\frac{\lambda k_n}{g_n}\right) k_n - \frac{\tau_{th}}{PL} = 0. \tag{6}$$

Proof: As the MI is concave, the objective function in Eq. (3) is also concave. Also, the constraints in Eq. (4) are linear functions of the power. Consequently, the optimization problem is convex. The Slater condition is satisfied with any positive power, $p_n > 0$, that satisfies the interference constraint. Therefore, the Karush-Kuhn-Tucker (KKT) conditions are necessary and sufficient for the optimal solution. The Lagrangian for the primal problem is derived as

$$L(\mathbf{p}, \lambda, \boldsymbol{\nu}) = -\sum_{n=1}^{N} I(p_n g_n) + \lambda\left(\sum_{n=1}^{N} J_n(d_n, p_n) - \frac{\tau_{th}}{PL}\right) - \nu_n p_n. \tag{7}$$

The KKT conditions are as follows. Gradient of Lagrangian with respect to $p_n^\star$ vanishes

$$-\frac{\partial I(p_n^\star g_n)}{\partial p_n^\star} + \lambda \frac{\partial J_n}{\partial p_n^\star} - \nu_n = 0, \tag{8}$$

$$\nu_n \geq 0, \quad p_n^\star \geq 0, \quad \lambda \geq 0, \quad \nu_n p_n^\star = 0. \tag{9}$$

Using the fact that $\dfrac{\partial I(p_n^\star g_n)}{\partial p_n^\star} = g_n \text{ mmse}(p_n^\star g_n)$, Eq. (8) can be rewritten as

$$-g_n \text{ mmse}(p_n^\star g_n) + \lambda k_n - \nu_n = 0. \tag{10}$$

From Eq. (9) and Eq. (10) we have

$$\frac{g_n}{k_n} \text{ mmse}(p_n^\star g_n) \leq \lambda, \tag{11}$$

$$p_n^\star \{\lambda k_n - g_n \text{ mmse}(p_n^\star g_n)\} = 0. \tag{12}$$

Consequently, if $p_n^\star > 0$ then from Eq. (12) we have $\lambda = \frac{g_n}{k_n} \text{ mmse}\left(p_n^\star g_n\right)$, therefore

$$\text{mmse}(p_n^\star g_n) = \frac{\lambda k_n}{g_n}, \tag{13}$$

$$p_n^\star = \frac{1}{g_n} \text{ mmse}^{-1}\left(\frac{\lambda k_n}{g_n}\right). \tag{14}$$

Since $\text{mmse}\left(p_n^\star g_n\right) < 1$ when $p_n^\star > 0$, we obtain from Eq. (11) $\frac{g_n}{k_n} > \lambda$. On the other hand, as $\text{mmse}(0) = 1$, if $p_n^\star = 0$, we have from Eq. (11) $\frac{g_n}{k_n} \leq \lambda$. ■

We denote the total transmit optimal power ($P^\star = \sum_{n=1}^{N} p_n^\star$) with Gaussian inputs as $P_G^\star$ and with FSA inputs as $P_{FSA}^\star$. In Fig. 1 (dashed line), we plot power saving, i.e., $P_G^\star - P_{FSA}^\star$ for FSA inputs in CR networks through Monte Carlo simulations. For practical reasons, we adopt LTE parameters and assume the available bandwidth for the SU transmission is 10 MHz which is divided into 50 resource blocks (RBs) [11], whereas τ_{th} is assumed to be equivalent to thermal noise per RB. We observe from Fig. 1 that, there is significant power saving by using the proposed optimal power $P_{FSA}^\star$ compared to the optimal power derived in [3], that assumes the Gaussian input $P_G^\star$. For distance between SU transmitter and PU reciever ranging between 50m to 100m, the transmit power saving is $65-91\%$, $49-87\%$ and $13-69\%$ with BPSK, QPSK and 16-QAM inputs, respectively. Motivated by these promising results, we analyze theoretically the power saving in the next section.

IV. Theoretical Analysis of Power Saving

Theorem 2: The power saving for a Rayleigh channel distribution by using the proposed optimal power ($P_F^\star$) compared to the conventional power allocation scheme ($P_G^\star$) is given by

$$\bar{P}_{saving}^\star(\mathbf{g}) = \bar{P}^\star(\mathbf{g}, G) - \bar{P}^\star(\mathbf{g}, F), \tag{15}$$

where

$$\bar{P}^\star(\mathbf{g}, F) \approx \sum_{n=1}^{N} \Bigg[A\left(\frac{\sqrt{2}\Gamma(\frac{1}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2\sigma}\right) + B\left(\frac{2\Gamma(1, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + C\left(\frac{2\sqrt{2}\sigma\Gamma(\frac{3}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + D\left(\frac{4\sigma^2\Gamma(2, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right)\Bigg], \tag{16}$$

and

$$\bar{P}^\star(\mathbf{g}, G) = \sum_{n=1}^{N} \left[\frac{\Gamma(1, \frac{k_n^2\lambda^2}{2\sigma^2})}{\lambda k_n} - \frac{\Gamma(\frac{1}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{\sqrt{2}\sigma}\right], \tag{17}$$

where $A = \left(f(a) - af'(a) + \frac{a^2 f''(a)}{2} - \frac{a^3 f'''(a)}{6}\right)$, $B = \left(f'(a) - af''(a) + \frac{a^2 f'''(a)}{2}\right)$, $C = \left(\frac{f''(a)}{2} - \frac{af'''(a)}{2}\right)$, $D =$

$\frac{f'''(a)}{6}$, $f(a) = W(\alpha_n a^2)$, $f'(a)$ denotes the derivative of f evaluated at the point a, σ is channel statistic parameter for Rayleigh distribution, $\Gamma(.,.)$ is the incomplete gamma function, $\mathbf{g} = [g_1, ..., g_n]$ and d is the minimum distance for unit variance constellations, i.e., $d = 2$, $\sqrt{2}$ and $\sqrt{2/5}$ for BPSK, QPSK and 16-QAM, respectively. Notations G and F represent Gaussian and FSA input distributions.

Proof: The average optimal power with arbitrary input distributions can be obtained as

$$\bar{P}^\star(\mathbf{g}, S) = \sum_{n=1}^{N} \int_{k_n\lambda}^{\infty} p^\star(g_n, S) h(g_n) dg_n, \quad (18)$$

where $h(g_n)$ is a Probability Distribution Function (pdf) of the channel and for a Rayleigh fading channel, the pdf is $(g_n/\sigma^2)e^{-{g_n}^2/2\sigma^2}$. MMSE relationships for FSA and Gaussian input distributions are given by [6]

$$mmse_{(F)}(p_n^\star g_n) \approx U \frac{e^{\frac{-d^2}{4}(p_n^\star g_n)}}{\sqrt{p_n^\star g_n}}, \quad (19)$$

$$mmse_{(G)}(p_n^\star g_n) = \frac{1}{1 + p_n^\star g_n}, \quad (20)$$

where $U = \frac{\sqrt{\pi}}{d}, 1$ for M-PSK and M-QAM, respectively. To calculate $p_n^\star(g_n, F)$ and $p_n^\star(g_n, G)$, we substitute Eqs. (19) and (20) into Eq. (13). After some mathematical manipulations, we obtain

$$e^{\frac{d^2}{4}(p_n^\star g_n)} \sqrt{p_n^\star} = \frac{U\sqrt{g_n}}{\lambda k_n}, \quad (21)$$

$$p_n^\star(g_n, F) = \frac{2}{d^2 g_n} W\left(\frac{U^2 d^2 {g_n}^2}{2\lambda^2 k_n^2}\right), \quad (22)$$

$$p_n^\star(g_n, G) = \frac{1}{\lambda k_n} - \frac{1}{g_n}, \quad (23)$$

where $W(.)$ is the Lambert W function [12]. From Eq. (18), the optimal power for the FSA input can be derived as

$$\int_{k_n\lambda}^{\infty} p^\star(g_n, F) h(g_n) dg_n = \frac{2}{d^2\sigma^2} \int_{k_n\lambda}^{\infty} W\left(\alpha_n {g_n}^2\right) e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n, \quad (24)$$

where $\alpha_n = \frac{U^2 d^2}{2\lambda^2 k_n^2}$. To solve the Lambert W function, Taylor series is required. The right hand side of Eq. (24) will be

$$\approx \frac{2}{d^2\sigma^2}\left[A\int_{k_n\lambda}^{\infty} e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n + B\int_{k_n\lambda}^{\infty} g_n e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n + C\int_{k_n\lambda}^{\infty} {g_n}^2 e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n + D\int_{k_n\lambda}^{\infty} {g_n}^3 e^{\frac{-{g_n}^3}{2\sigma^2}} dg_n\right]. \quad (25)$$

According to [13]

$$\int_{u}^{\infty} x^m e^{-\beta x^r} dx = \frac{\Gamma(v, \beta u^r)}{r\beta^v}, \quad v = \frac{m+1}{r} \quad [\beta > 0, \quad v > 0, \quad r > 0 \quad u > 0]. \quad (26)$$

A closed form of Eq. (25) can be derived as

$$\approx A\left(\frac{\sqrt{2}\Gamma(\frac{1}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2\sigma}\right) + B\left(\frac{2\Gamma(1, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + C\left(\frac{2\sqrt{2}\sigma\Gamma(\frac{3}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + D\left(\frac{4\sigma^2\Gamma(2, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right). \quad (27)$$

By substituting Eq. (27) into Eq. (18), we obtain Eq. (16). To obtain $f(a), f'(a), f''(a), f'''(a)$ in Eq. (27), we define the function then take its derivatives as follows

$$f(g_n) = W(\alpha_n {g_n}^2), \quad (28)$$

$$f'(g_n) = \frac{2W(\alpha_n {g_n}^2)}{g_n\left[W(\alpha_n {g_n}^2) + 1\right]}, \quad (29)$$

$$f''(g_n) = \frac{-2W(\alpha_n {g_n}^2)\left[W(\alpha_n {g_n}^2)^2 + W(\alpha_n {g_n}^2) - 1\right]}{{g_n}^2\left[W(\alpha_n {g_n}^2) + 1\right]^3}, \quad (30)$$

$$f'''(g_n) = \frac{4W(\alpha_n {g_n}^2)^2}{{g_n}^3\left[W(\alpha_n {g_n}^2) + 1\right]^5} \left[W(\alpha_n {g_n}^2)^3 + 4W(\alpha_n {g_n}^2)^2 + 3W(\alpha_n {g_n}^2) - 6\right]. \quad (31)$$

By substituting the value of α_n in Eqs. (28), (29), (30) and (31), required values can be calculated. By substituting Eq. (23) into (18) and applying Eq. (26), the optimal power for Gaussian inputs can be derived as

$$\begin{aligned}\int_{k_n\lambda}^{\infty} p^\star(g_n, G) h(g_n) dg_n &= \frac{1}{\sigma^2\lambda k_n}\int_{k_n\lambda}^{\infty} g_n e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n - \frac{1}{\sigma^2}\int_{k_n\lambda}^{\infty} e^{\frac{-{g_n}^2}{2\sigma^2}} dg_n \\ &= \frac{\Gamma(1, \frac{k_n^2\lambda^2}{2\sigma^2})}{\lambda k_n} - \frac{\Gamma(\frac{1}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{\sqrt{2}\sigma}.\end{aligned} \quad (32)$$

By substituting Eq. (32) into (18), we obtain Eq. (17). In Eq. (32) and Eq. (27), k_n, d and σ are constant values, however, λ is dependent on channel gain. Therefore, we will calculate λ numerically through the following equation

$$\sum_{n=1}^{N} \int_{k_n\lambda}^{\infty} p^\star(g_n, S) k_n h(g_n) dg_n = \frac{\tau_{th}}{PL}. \quad (33)$$

By substituting Eq. (22) into Eq. (33) and after doing the same manipulations as in Eqs. (24), (25) and (26), we can obtain the value of λ for the FSA input using the following equation

$$\sum_{n=1}^{N}\left[A\left(\frac{\sqrt{2}\Gamma(\frac{1}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2\sigma}\right) + B\left(\frac{2\Gamma(1, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + C\left(\frac{2\sqrt{2}\sigma\Gamma(\frac{3}{2}, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right) + D\left(\frac{4\sigma^2\Gamma(2, \frac{k_n^2\lambda^2}{2\sigma^2})}{d^2}\right)\right] = \frac{\tau_{th}}{PL}. \quad (34)$$

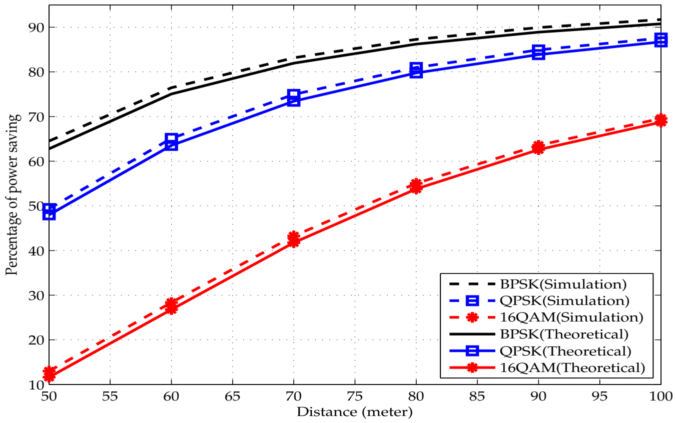

Fig. 1. Comparison between theoretical and simulation results.

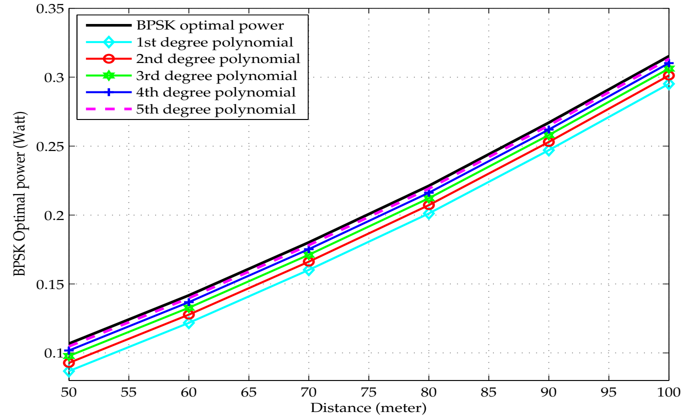

Fig. 2. Taylor series approximation.

Similarly, by substituting Eq. (23) into Eq. (33) and after doing the same manipulations as in Eq. (32), we can obtain the value of λ for the Gaussian input using the following equation

$$\sum_{n=1}^{N}\left[\frac{\Gamma(1,\frac{k_n^2\lambda^2}{2\sigma^2})}{\lambda}-\frac{k_n\Gamma(\frac{1}{2},\frac{k_n^2\lambda^2}{2\sigma^2})}{\sqrt{2}\sigma}\right]=\frac{\tau_{th}}{PL}. \qquad (35)$$

By substituting the values of k_n, N, τ_{th}, PL and σ, λ in Eq. (34) and Eq. (35) can be calculated numerically. ■

V. Evaluation of Theoretical Analysis

As discussed in Sec. III, our simulation study has shown that the proposed optimal power allocation scheme has achieved significant power saving compared to the optimal power under the Gaussian input. Fig. 1 shows the comparison of analytical (solid line) and simulated (dashed line) power saving. σ in Eqs. (16) and (17) has been calculated from the empirical Rayleigh distribution and implemented in the simulation. One can see that theoretical results coincide well with the simulation results, and the discrepancy is marginal. The minor difference follows from the fact that we used approximated values of MMSE in Eq. (19) in order to calculate the optimal power under the FSA input. It can be concluded that for given channel statistics, the theoretical analysis can be used to derive an average optimal power allocation and estimate power saving without running time-consuming Monte-Carlo simulations.

To evaluate the accuracy of using Taylor expansion, Fig. 2 depicts the optimal power of BPSK and the optimal power achieved by different degrees of Taylor polynomials. It is clear from the figure that the 5^{th} degree of Taylor polynomials approximately match the exact value and thus can be used to calculate the theoretical optimal power under arbitrary input distributions as well as the achieved power saving using the proposed power allocation scheme.

VI. Conclusion

In this paper, we have derived theoretically an optimal power allocation scheme for FSA inputs as opposed to traditional Gaussian inputs, using convex optimization technique. Our proposed scheme achieves significant power saving in comparison to the optimal power derived under the Gaussian input assumption, consequently leading to improved energy efficiency. Furthermore, the results obtained from the theoretical analysis of power saving scheme match well with the simulation results. Our analysis provides a theoretical framework for the derivation of the optimal power allocation and calculation of power saving under FSA input distributions.

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