# Joint Power Allocation and Constellation Design for Cognitive Radio Systems

Taimour Aldalgamouni, Mehmet Cagri Ilter, and Halim Yanikomeroglu

***Abstract*—A cognitive radio is a smart software-defined radio that can adapt its transmission parameters, such as transmit power level and modulation type, based on the wireless channel conditions. In this paper, we introduce a joint power allocation and constellation design algorithm for cognitive radios assuming spectrum sensing imperfections. The proposed algorithm minimizes the symbol error rate of the secondary user by designing optimized 2-D constellation points and assigning transmit power levels. The constellation points are assumed to be equally probable with zero-mean and unit average symbol energy. The transmit power levels are assigned such that they do not exceed a predefined maximum transmit power threshold, and that the interference resulting from the secondary user to the primary user does not exceed a predefined value. The outcomes of the proposed algorithm, which are constellation points and transmit power levels, can be stored in a lookup table that the secondary user can access to adapt its transmission parameters to the environment based on sensing decisions, maximum transmit powers, and interference levels allowed by the primary user. Numerical results are provided to show the symbol error rate performance of the designed constellation points and compared to the performance of the conventional square grid M-ary quadrature amplitude modulation under the same operational parameters.**

***Index Terms*—Cognitive radio, constellation design, power allocation.**

## I. Introduction

Future wireless networks such as the fifth generation (5G) networks are expected to support large volume of heterogeneous wireless traffic that is generated by diverse wireless applications with different quality of service (QoS) requirements in terms of data rate and latency. Moreover, the wireless traffic is not evenly distributed in space or time. Current cellular networks operate over licensed frequency bands which are both expensive and scarce and optimized for delay-sensitive applications like voice services. The large volume of wireless traffic requires large bandwidth, however, the uneven distribution of traffic can cause the bandwidth to be under-utilized for average traffic loads or be insufficient for peak traffic loads and therefore cost ineffective. The heterogeneity of the traffic and the diversity of QoS requirements can cause some applications with high volume and delay-insensitive traffic such as the multimedia traffic to be cost-inefficient to gain momentum in current networks.

Although the licensed spectrum is scarce, it has been reported in [1] that some of the licensed bands are significantly under-utilized. Cognitive radio (CR) is an intelligent software-defined radio that can adaptively change some of its transmission parameters such as transmit power and modulation through learning about its transmission environment [2]. CR can improve the utilization of the licensed spectrum by allowing a secondary user (SU) to dynamically access the licensed spectrum without degrading the QoS of the licensed user also known as the primary user (PU). Therefore, CR has been identified as a promising technology that can address the above mentioned challenges that can face future wireless networks. For example, wireless networks can lease the under-utilized spectrum to accommodate high traffic volumes during peak hours or to provide low cost opportunistic multimedia services [3].

In sensing-based spectrum sharing (SSS) CR networks [4], the SU first senses the licensed spectrum for PU activity. If the PU is inactive, then the SU transmits with high power to achieve higher transmission rates. If PU activity is detected, then the SU transmits with lower power to avoid exceeding the interference levels accepted by the PU.

Several research papers, [5]–[8], have addressed the effects of modulation type and power allocation on the performance of CR systems. In [5], closed-form expressions for the symbol error rate (SER) of M-ary quadrature amplitude modulation (MQAM) in CR have been provided assuming imperfect spectrum sensing. In [6], an algorithm that assigns power levels and MQAM constellation size to maximize the capacity of SU in CR systems under transmit power, interference levels, and bit error rate constraints are represented. Adaptive modulation and power control algorithm that maximizes the life time of a cognitive wireless sensor network has been proposed in [7]. A power allocation framework that maximizes the energy efficiency in SSS CR systems has been presented in [8].

Choosing the optimal constellation points that satisfy some performance criteria has been a fundamental problem in digital communications for many decades. Many research papers have addressed the problem of constellation design for different systems and for different objectives and constraints [9]–[12]. The authors in [9] design 3-dimensional constellations for spatial modulation to enhance the reliability of transmission. In [10], the authors design constellation points for multiple input multiple output (MIMO) visible light communications (VLC) that are both channel adaptive and space collaborative. In [11], the authors design multi-dimensional constellations for orthogonal space time block codes by minimizing the block SER. Design of optimum non-uniform QAM constellations for cooperative relaying systems has been introduced in [12]. However, none of the previous studies has considered constellation design for CR systems.

In this paper, we introduce a joint power allocation and constellation design algorithm for CRs taking into account spectrum sensing imperfections. The proposed algorithm selects the optimal constellation points and transmit power levels that minimize the average SER of the SU. The selected optimal constellation points are assumed to be equally probable and constrained to have zero-mean and an average energy of unity. The selected transmit power levels are constrained to be less than a pre-defined maximum transmit power level and such that the interference caused by the SU at the receiver of the PU does not exceed a pre-defined threshold. The optimal constellation points

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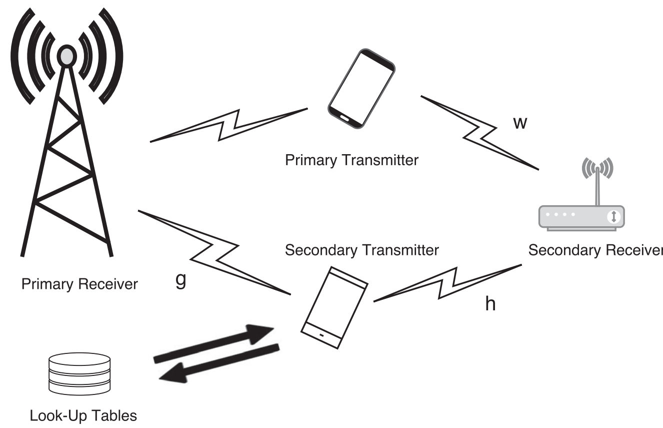


Fig. 1. Cognitive radio system model.

and transmit power levels can be stored in a lookup table that the SU can access in order to reconfigure its transmission parameters based on sensing decisions, maximum transmit power level, and interference levels allowed by the PU. Numerical results are provided to show the SER performance of the designed constellation points and compared to the performance of the conventional square grid MQAM under the same operational parameters.

The rest of the paper is organized as follows. The system model is described in Section II. In Section III, the SER is analyzed. The joint power allocation and constellation design is introduced in Section IV. Numerical results are presented in Section V, while Section VI concludes the paper.

## II. System Model

In this paper, we consider CR network of several SUs that geographically coexists with multiple PUs. PUs are usually provisioned to operate over non-overlapping frequency bands and hence it is safe to assume only one PU. It is also assumed that no two SUs can transmit at the same time. This can be achieved through the implementation of a medium access (MAC) protocol to coordinate the transmissions of the SUs inside the CR network [13]. Because of the aforementioned assumptions, the system can be reduced to only one SU and one PU as shown in Fig. 1 and hence the index of the SU will be dropped in the sequel. The SU starts by sensing the channel which is modeled as hypothesis testing where $\mathcal{H}_0$ denotes the hypothesis that the PU is not using the channel (the channel is idle) and $\mathcal{H}_1$ denotes the hypothesis that the PU is active and using the channel (the channel is busy). Many channel sensing techniques like energy detection and match filtering detection have been proposed and analyzed in the literature. All of the existing channel sensing techniques suffer from imperfections which can be characterized by false alarms and missed detections. Denoting the sensing decisions of the SU that the PU is active or inactive by $\hat{\mathcal{H}}_1$ and $\hat{\mathcal{H}}_0$, respectively, then the probability of detection and the probability of false alarm can be expressed in terms of conditional probabilities as

$$P_d = Pr\{\hat{\mathcal{H}}_1/\mathcal{H}_1\}, \tag{1}$$

$$P_f = Pr\{\hat{\mathcal{H}}_1/\mathcal{H}_0\}, \tag{2}$$

respectively. In SSS systems, the SU transmits with an average power $P_1$, if it detects PU activity on the channel, while it transmits with an average power $P_0$ if the channel is detected as idle. Based on the maximum average transmit power and maximum allowable average interference from the secondary transmitter at the primary receiver, the following constraints are imposed:

$$\begin{aligned} P_1 &\le P_{pk}, \\ P_0 &\le P_{pk}, \\ P_1 &\le P_0, \\ (1-P_d)P_0E\{|g|^2\} + P_dP_1E\left[|g|^2\right] &\le Q_{\text{avg}}, \end{aligned} \tag{3}$$

where $P_{pk}$ is the maximum allowable transmit power, $E[\cdot]$ is the expectation operator, $Q_{\text{avg}}$ is the maximum allowable average interference at the PU receiver, $g$ is the fading channel parameter between the secondary transmitter and the primary receiver which we assume to be a complex Gaussian random variable with zero-mean and unity variance. Based on the true state of the PU and the sensing decision of the SU, there will be four different input-output relationships:

I A busy channel is sensed as busy (correct detection)

$$y = \sqrt{P_1}hs + n + w, \tag{4}$$

which happens with a probability

$$\begin{aligned} Pr(\hat{\mathcal{H}}_1, \mathcal{H}_1) &= Pr(\hat{\mathcal{H}}_1/\mathcal{H}_1)Pr(\mathcal{H}_1) \\ &= P_dPr(\mathcal{H}_1), \end{aligned} \tag{5}$$

and is assumed to have a SER of $\mathsf{SER}_I$.

II A busy channel is sensed as idle (missed detection)

$$y = \sqrt{P_0}hs + n + w, \tag{6}$$

which happens with a probability

$$\begin{aligned} Pr(\hat{\mathcal{H}}_0, \mathcal{H}_1) &= Pr(\hat{\mathcal{H}}_0/\mathcal{H}_1)Pr(\mathcal{H}_1) \\ &= (1-P_d)Pr(\mathcal{H}_1), \end{aligned} \tag{7}$$

and is assumed to have a SER of $\mathsf{SER}_{II}$.

III An idle channel is sensed as busy ( false alarm)

$$y = \sqrt{P_1}hs + n, \tag{8}$$

which happens with a probability

$$\begin{aligned} Pr(\hat{\mathcal{H}}_1, \mathcal{H}_0) &= Pr(\hat{\mathcal{H}}_1/\mathcal{H}_0)Pr(\mathcal{H}_0) \\ &= P_fPr(\mathcal{H}_0), \end{aligned} \tag{9}$$

and is assumed to have a SER of $\mathsf{SER}_{III}$.

IV An idle channel is sensed as idle (correct detection)

$$y = \sqrt{P_0}hs + n, \tag{10}$$

which happens with a probability

$$\begin{aligned} Pr(\hat{\mathcal{H}}_0, \mathcal{H}_0) &= Pr(\hat{\mathcal{H}}_0/\mathcal{H}_0)Pr(\mathcal{H}_0) \\ &= (1-P_f)Pr(\mathcal{H}_0), \end{aligned} \tag{11}$$

and is assumed to have an a SER of $\mathsf{SER}_{IV}$.

In the above, $y$ is the received signal at the secondary receiver, $h$ is a complex Gaussian random variable with zero-mean and a variance of $\sigma_h^2$ that represents the fading channel between the transmitter and the receiver of the SU. $s$ is the transmitted symbol, $n$ is a complex Gaussian random variable with zero-mean and a variance of $\sigma_n^2$ that represents the additive white Gaussian noise (AWGN) at the secondary receiver. $w$ represents the interference caused by the PU transmitter at the secondary receiver which is assumed to be a complex Gaussian random variable with zero-mean and a variance of $\sigma_w^2$.

## III. Symbol Error Rate Analysis

The SER for CRs with channel sensing imperfections can be expressed as a weighted sum of the SER of the different input-output relationships described by (4), (6), (8), and (10) as

$$\mathsf{SER} = P_d Pr(\mathcal{H}_1)\mathsf{SER}_I + (1-P_d)Pr(\mathcal{H}_1)\mathsf{SER}_{II} + P_f Pr(\mathcal{H}_0)\mathsf{SER}_{III} + (1-P_f)Pr(\mathcal{H}_0)\mathsf{SER}_{IV}.$$

For arbitrary two-dimensional constellations with zero-mean, average symbol energy of unity, and uniform signalling over Rayleigh fading channels perturbed by AWGN, the average SER can be expressed as [14]

$$P_e = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{l=0,l\neq k}^{M-1}\sum_{t=1}^{T_l} \pm E\left[\mathrm{Q}\left(\pm\overline{\mathcal{L}}_{l,p_t}(a_k)\sqrt{2\gamma}, \pm\overline{\mathcal{L}}_{l,p_{t+1}}(a_k)\sqrt{2\gamma}; \pm\Re\left[c_{l,p_t}c^*_{l,p_t}\right]\right)\right], \tag{12}$$

where $\overline{\mathcal{L}}_{k,l}(a_k) = (\Re[a_k c^*_{k,l}] + d_{k,l})/|c_{k,l}|,\ c_{k,l} = a_l - a_k,\ d_{k,l} = \frac{1}{2}[|a_k|^2 - |a_l|^2]$, and $a_k$ is a constellation point taken from the alphabet $\mathcal{A} = \{a_0, \ldots, a_{M-1}\}$. $T_k$ is the number of non-redundant inequalities that define the decision region for the symbol $a_k$. $\Re[\cdot]$ is the real part and $Q(a,b,\rho)$ is the complementary cumulative distribution function (CDF) of a bivariate Gaussian variable [14]. The expectation term that appears in (12) can be expressed assuming that the signal-to-noise ratio (SNR) denoted by $\gamma$ is Rayleigh distributed as in [14]

$$E\left[Q\left(\alpha_1\sqrt{\gamma}, \alpha_2\sqrt{\gamma}; \rho\right)\right] = f\left(\alpha_1, \alpha_2, \rho, \overline{\gamma}, 1\right), \tag{13}$$

where $\overline{\gamma}$ is the average SNR and

$$f\left(\alpha_1, \alpha_2, \rho, \overline{\gamma}, 1\right) = A\left(\frac{\alpha_1^2\overline{\gamma}}{2}, v\left(\alpha_1, \alpha_2, \rho\right), 1\right) + A\left(\frac{\alpha_2^2\overline{\gamma}}{2}, v\left(\alpha_2, \alpha_1, \rho\right), 1\right), \tag{14}$$

where

$$v(a,b,\rho) = \begin{cases} \tan^{-1}\left(\dfrac{a\sqrt{1-\rho^2}}{b-a\rho}\right), & \rho a \le b, \\ \tan^{-1}\left(\dfrac{a\sqrt{1-\rho^2}}{b-a\rho}\right) + \pi, & b < a\rho, \\ \tan^{-1}\left(\sqrt{\dfrac{1+\rho}{1-\rho}}\right), & a = b = 0, \end{cases} \tag{15}$$

and

$$A(a,\phi,1) = \frac{1}{2\pi}\left(\phi - \sqrt{\frac{a}{a+1}}\tan^{-1}\left(\sqrt{\frac{a+1}{a}}\tan(\phi)\right)\right). \tag{16}$$

The average SER for each of the four input-output relationships mentioned above can be written as in (17)–(20)

$$\overline{\mathsf{SER}}_I = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{l=0,l\neq k}^{M-1}\sum_{t=1}^{T_l} \pm\left(A\left(\frac{\alpha_1^2 P_1 E\left\{|h|^2\right\}}{2\left(\sigma_n^2+\sigma_w^2\right)}, v\left(\alpha_1,\alpha_2,\rho\right), 1\right) + A\left(\frac{\alpha_2^2 P_1 E\left\{|h|^2\right\}}{2\left(\sigma_n^2+\sigma_w^2\right)}, v\left(\alpha_2,\alpha_1,\rho\right), 1\right)\right). \tag{17}$$

$$\overline{\mathsf{SER}}_{II} = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{l=0,l\neq k}^{M-1}\sum_{t=1}^{T_l} \pm\left(A\left(\frac{\alpha_1^2 P_0 E\left\{|h|^2\right\}}{2\left(\sigma_n^2+\sigma_w^2\right)}, v\left(\alpha_1,\alpha_2,\rho\right), 1\right) + A\left(\frac{\alpha_2^2 P_0 E\left\{|h|^2\right\}}{2\left(\sigma_n^2+\sigma_w^2\right)}, v\left(\alpha_2,\alpha_1,\rho\right), 1\right)\right). \tag{18}$$

$$\overline{\mathsf{SER}}_{III} = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{l=0,l\neq k}^{M-1}\sum_{t=1}^{T_l} \pm\left(A\left(\frac{\alpha_1^2 P_1 E\left\{|h|^2\right\}}{2\sigma_n^2}, v\left(\alpha_1,\alpha_2,\rho\right), 1\right) + A\left(\frac{\alpha_2^2 P_1 E\left\{|h|^2\right\}}{2\sigma_n^2}, v\left(\alpha_2,\alpha_1,\rho\right), 1\right)\right). \tag{19}$$

$$\overline{\mathsf{SER}}_{IV} = \frac{1}{M}\sum_{k=0}^{M-1}\sum_{l=0,l\neq k}^{M-1}\sum_{t=1}^{T_l} \pm\left(A\left(\frac{\alpha_1^2 P_0 E\left\{|h|^2\right\}}{2\sigma_n^2}, v\left(\alpha_1,\alpha_2,\rho\right), 1\right) + A\left(\frac{\alpha_2^2 P_0 E\left\{|h|^2\right\}}{2\sigma_n^2}, v\left(\alpha_2,\alpha_1,\rho\right), 1\right)\right). \tag{20}$$

and the overall average SER can be written as

$$\overline{\mathsf{SER}} = P_d Pr(\mathcal{H}_1)\overline{\mathsf{SER}}_I + (1-P_d)Pr(\mathcal{H}_1)\overline{\mathsf{SER}}_{II} + P_f Pr(\mathcal{H}_0)\overline{\mathsf{SER}}_{III} + (1-P_f)Pr(\mathcal{H}_0)\overline{\mathsf{SER}}_{IV}. \tag{21}$$

## IV. Joint Power Allocation and Constellation Design

In this section, we will formulate the power allocation and constellation design problem as an optimization problem that minimizes the average SER of the SU taking spectrum sensing imperfections into considerations as follows:

$$\min_{\{a_0,\ldots,a_{M-1},P_0,P_1\}} \quad \overline{\mathsf{SER}} \tag{22a}$$

$$\text{subject to} \quad P_1 \le P_{pk}, \tag{22b}$$

$$P_0 \le P_{pk}, \tag{22c}$$

$$P_1 \le P_0, \tag{22d}$$

$$(1-P_d)P_0 E\{|g|^2\} + P_d P_1 E\{|g|^2\} \le Q_{\mathrm{avg}}, \tag{22e}$$

$$\sum_{k=0}^{M-1} a_k = 0, \tag{22f}$$

$$\frac{1}{M}\sum_{k=0}^{M-1}|a_k|^2 = 1. \tag{22g}$$

Due to the non-linearity and the non-convexity of the optimization problem, we will solve it using the MATLAB function fmincon with interior-point algorithm which does not guarantee global minimum but can result in local minimum. It is noteworthy mentioning here that there is no single set of constellation points and power levels that is optimal for all values of average interference levels, probability of detection,

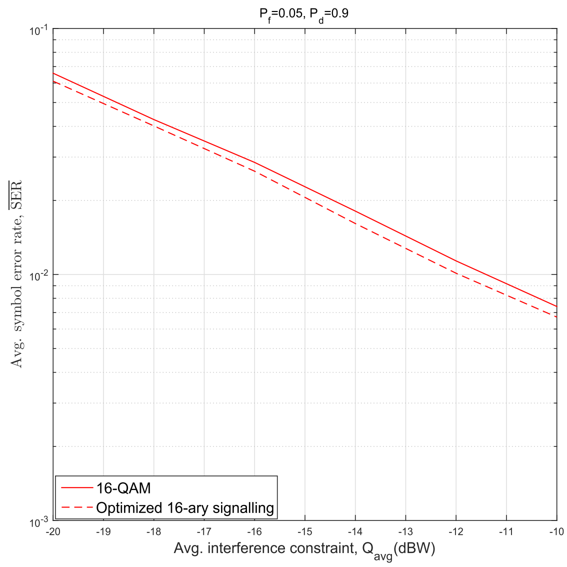


Fig. 2. Average SER for 16-ary signaling versus average interference constraint $(Q_{\text{avg}})$ in the SSS scheme.

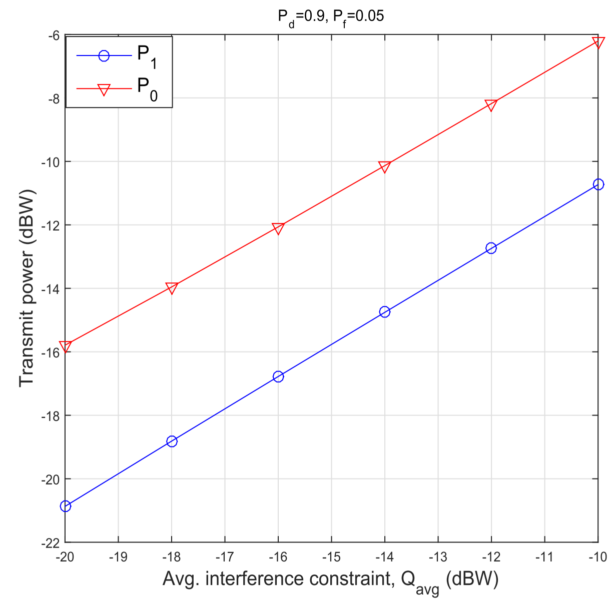


Fig. 3. Power allocation for 16-ary signaling versus average interference constraint $(Q_{\text{avg}})$ in the SSS scheme.

and probability of false alarm. Hence, the joint power allocation and constellation design algorithm will be run for every combination of $Q_{\text{avg}}$, $P_d$, and $P_f$.

## V. Numerical Results

In this section, we will examine the performance of the proposed algorithm for a wide range of the operating parameters $Q_{\text{avg}}$, $P_d$, $P_f$, and $P_{pk}$ for 16-ary modulation alphabet. The optimization algorithm can be run off-line for all possible values of the operating parameters. The results of the optimization algorithm in terms of constellation points and power levels can be stored in a lookup table. The SU has first to determine its operating parameters. It is assumed here that the SU can determine its own probabilities of detection and false alarm. For example, the probabilities of detection and false alarm in energy detectors over Rayleigh fading channels can be calculated as in [15] which requires the knowledge of the detection threshold along with the value of the average SNR. The average SNR can be estimated using a training sequence or other techniques as shown in [16]. It is also assumed that the SU is aware of the maximum allowable average interference levels $(Q_{\text{avg}})$ that the PU can tolerate along with its own maximum allowable transmit power $(P_{pk})$. The SU then selects from the lookup table the optimum constellation points and power levels.

In all results, we have assumed SSS cognitive radio systems. The following values have been assumed in all results unless stated explicitly. It is assumed that the variance of the background noise at the secondary receiver is $\sigma_n^2 = 10^{-4}$. Also, the interference caused by the primary transmitter at the secondary receiver is assumed to be Gaussian with a variance of $\sigma_w^2 = 10^{-4}$. The fading channel between the transmitter and the receiver of the SU is assumed to be Rayleigh distributed with $E\left\{|h|^2\right\} = 1$. Also, the fading channel between the secondary transmitter and the primary receiver is assumed to be Rayleigh distributed with $E\left\{|g|^2\right\} = 1$. The PU is assumed to be active and using the channel with a probability of 0.4 which means that $Pr(\mathcal{H}_1) = 0.4$ and $Pr(\mathcal{H}_0) = 0.6$. The SU is assumed to have a peak transmit power of $P_{pk} = 4$ dBW. The SER of the optimized constellations is given and compared to that of the conventional square 16-QAM for the same optimized power levels.

Fig. 2 shows the average SER of 16-ary signalling with $P_d = 0.9$, $P_f = 0.05$ and for different values of $Q_{\text{avg}}$. The figure shows that the optimized constellations perform better than the square 16-QAM over the whole range of $Q_{\text{avg}}$. At an average SER of $10^{-2}$, the optimized constellation has 0.5 dB improvement over the square 16-QAM for the un-coded system. This means the optimized constellations provide extra protection for the PU against the interference caused by the SU. Fig. 3 shows the power allocation for the 16-ary case with $P_d = 0.9$, $P_f = 0.05$ and for different values of $Q_{\text{avg}}$. The figure shows that $P_1$ is less than $P_0$ for the whole range of $Q_{\text{avg}}$ which can be justified by that the secondary transmitter transmits with the power $P_1$ when primary activity is sensed on the channel and hence the SU has to transmit with lower power to avoid causing excessive interference to PU. It also shows that both $P_1$ and $P_0$ increase with $Q_{\text{avg}}$ which means that the PU can tolerate higher values of interference.

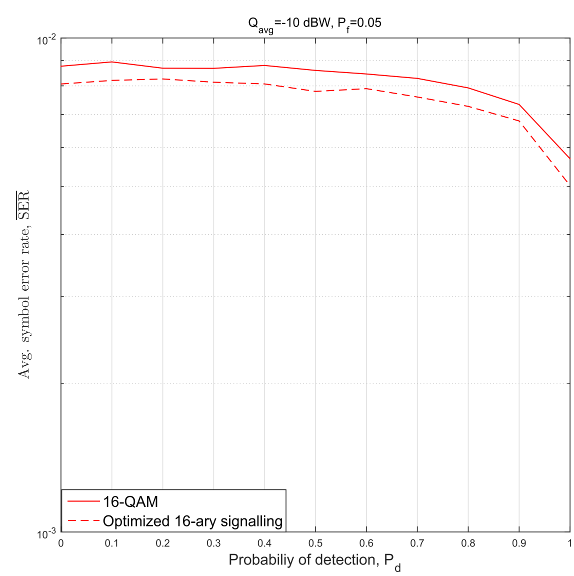


Fig. 4. Average SER for 16-ary signaling versus probability of detection $(P_d)$ in the SSS scheme.

Figs. 4 and 5 show the average SER and power allocation for the 16-ary case respectively with $Q_{\text{avg}} = -10$ dBW, $P_f = 0.05$, and for

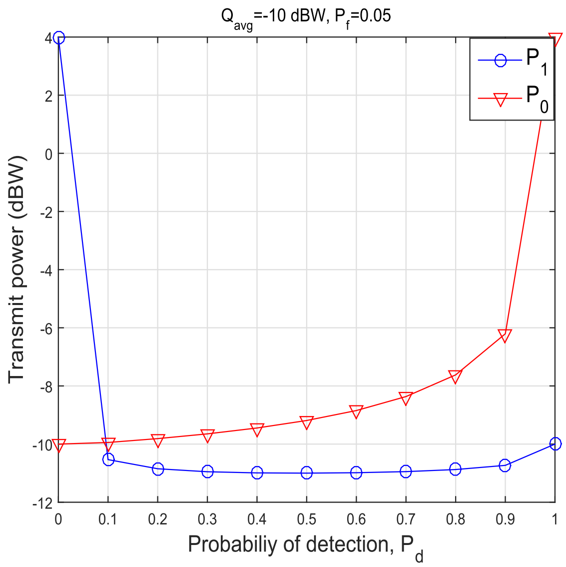


Fig. 5. Power allocation for 16-ary signaling versus probability of detection $(P_d)$ in the SSS scheme.

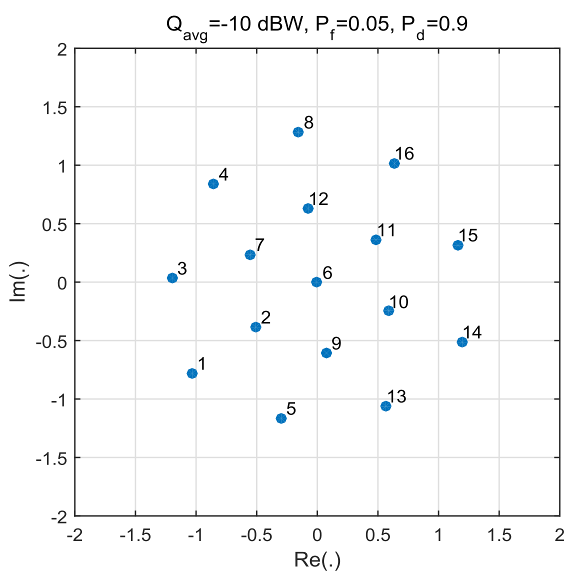


Fig. 6. Optimized 16-ary constellations for $P_f = 0.05$, $Q_{\text{avg}} = -10$ dBW, and $P_d = 0.9$.

different values of $P_d$. Fig. 4 shows that the optimized constellations have lower average SER compared to the square 16-QAM for the whole range of $P_d$ which means that the optimized constellations provide extra protection for the system against detection imperfections at the same SER or that for the same value of $P_d$, the system operates at a lower average SER. The poor performance of the average SER at low values of probability of detection ($P_d < 0.6$) in Fig. 4 is because the SU cannot transmit with high power when the channel is idle as shown in Fig. 5. Fig. 5 shows that $P_0$ increases rapidly after $P_d = 0.6$ and is equal to $P_{pk}$ when $P_d = 1$. This can be justified by constraints (22b)–(22e) which can be used to show that $P_0 \leq \min(\frac{Q_{\text{avg}}}{1-P_d}, P_{pk})$. Similarly, (22b)–(22e) can be used to show that $P_1 \leq \min(\frac{Q_{\text{avg}}}{P_d}, P_{pk})$ which justifies why $P_1 = P_{pk}$ at $P_d = 0$ and $P_1 = Q_{\text{avg}}$ at $P_d = 1$. The optimized 16-ary constellation points for $P_f = 0.05$, $Q_{\text{avg}} = -10$ dBW, and $P_d = 0.9$ are shown in Fig. 6. Fig. 6 shows that the constellation points are irregular which can increase the complexity of decoding [17]. However, this should not be considered as a shortcoming of the proposed algorithm given the advanced signal processing capabilities of the available radio transceivers.

## VI. Conclusion

In this paper, we have introduced a joint power allocation and constellation design algorithm for CR systems. The proposed algorithm assigns power levels and constellation points that minimize the average SER of the SU assuming spectrum sensing imperfections subject to transmit power and interference constraints. The results showed that the optimized constellations outperform the conventional square M-QAM constellations in terms of average SER for all values of probability of detection, probability of false alarm, and average interference.

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