Antenna Selection in Interference-Constrained Underlay Cognitive Radios: SEP-Optimal Rule and Performance Benchmarking

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***Abstract*—In the underlay mode of cognitive radio, secondary users are allowed to transmit when the primary is transmitting, but under tight interference constraints that protect the primary. However, these constraints limit the secondary system performance. Antenna selection (AS)-based multiple antenna techniques, which exploit spatial diversity with less hardware, help improve secondary system performance. We develop a novel and optimal transmit AS rule that minimizes the symbol error probability (SEP) of an average interference-constrained multiple-input-single-output secondary system that operates in the underlay mode. We show that the optimal rule is a non-linear function of the power gain of the channel from the secondary transmit antenna to the primary receiver and from the secondary transmit antenna to the secondary receive antenna. We also propose a simpler, tractable variant of the optimal rule that performs as well as the optimal rule. We then analyze its SEP with L transmit antennas, and extensively benchmark it with several heuristic selection rules proposed in the literature. We also enhance these rules in order to provide a fair comparison, and derive new expressions for their SEPs. The results bring out new inter-relationships between the various rules, and show that the optimal rule can significantly reduce the SEP.**

***Index Terms*—Cognitive radio, underlay, antenna selection, diversity techniques, fading channels, symbol error probability, average interference constraint.**

I. Introduction

RECENT studies reveal that electromagnetic spectrum allocations are often underutilized [1]. This coupled with an increase in the number of users demanding high data rates has created a scarcity of spectrum, and has led to the development of cognitive radio (CR) technology to address the scarcity. In one common paradigm of CR, two classes of users are defined, namely, primary users (PU) and secondary users (SU). A PU owns the license to use the spectrum. A SU can access the same spectrum as the primary, but is subject to constraints on the interference it causes to the PU so as to protect the PU.

Two types of CR access models are common in the literature, namely, overlay and underlay [2], [3]. In overlay CR, which has also been referred to as interweave CR in [4], the SU transmits only in the unused spectral regions. Hence, the SU does not cause any interference to the PU, except when it senses the spectrum incorrectly. Whereas, in underlay CR, the SU can access the spectrum even when the PU is transmitting. However, it is subject to tight constraints on the average or peak interference power that it can cause to the primary.

In order to limit the interference caused by the SU to the PU below a threshold, power allocation strategies were used in [5] to maximize SU capacity. In [6], multiple antennas were used to improve the performance of the SU; techniques such as transmit beamforming were explored. Multiple input multiple output (MIMO) antenna techniques for CR were investigated in [7]–[9]. However, one drawback of a multiple antenna system is that each antenna element requires an expensive radio frequency (RF) chain to process the signal to or from the antenna. For example, at the transmitter, the RF chain consists of a digital-to-analog converter, an upconverter, filters, and a power amplifier. While antenna elements are typically cheap, the RF chains constitute a significant portion of the total device cost.

To reduce the hardware costs of multiple antenna systems, a technique called antenna selection (AS) has been extensively studied [10], [11]. It uses fewer RF chains than the number of available antennas. A subset of antennas is selected as a function of the channel conditions and connected to the RF chains. Besides reducing hardware complexity, cost, and size, AS effectively harnesses the diversity benefits of multiple antennas [12]–[14]. Consequently, AS is now a part of next generation wireless standards such as the IEEE 802.11n and Long Term Evolution (LTE) [15].

Given its promise, AS has also been considered in CR systems [16]–[20], and has been shown to improve secondary system throughput. In the overlay mode, since the SU does not interfere with the PU, the rule for selecting which antenna to transmit from remains the same as for conventional AS systems, which are not subject to any interference constraint. For example, in a multiple input single output (MISO) system in which the secondary transmitter (STx) has L transmit antennas and the secondary receiver (SRx) has one receive antenna, the transmit antenna with the strongest channel power gain to the SRx antenna should be selected. We shall refer to this as the *unconstrained* AS rule henceforth. However, in the underlay mode, the primary interference constraint fundamentally changes the criterion on the basis of which

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the transmit antenna is selected. Intuitively, even though an antenna has a strong link to the SRx, it should not get selected if it causes significant interference to the primary receiver (PRx). Therefore, the selection rule must take into consideration both the STx to SRx (STx-SRx) and STx to PRx (STx-PRx) channel power gains.

Several rules for selecting an antenna in a MISO CR, such as the minimum interference (MI) rule and the maximum signal power to leak interference power ratio (MSLIR) rule, are proposed in [17] for an STx that transmits with a fixed power. The MI rule selects the antenna that causes the least interference to the primary. However, since the selection is done entirely on the basis of the STx-PRx channel gains, the secondary system does not benefit from antenna diversity. The MSLIR rule compromises between the MI and unconstrained rules, and selects the antenna with the highest ratio of STx-SRx and STx-PRx channel power gains. Note that all the above rules do not consider the average interference constraint and may not always be admissible. An AS rule similar to MSLIR rule is proposed in [20], but STx uses variable power to transmit. A difference selection (DS) rule is proposed in [18], [21]. It selects the antenna that maximizes a linear weighted difference of the STx-SRx and STx-PRx channel power gains. It outperforms the MSLIR rule in many scenarios. While the above rules are intuitive, they are ad hoc as they do not provably optimize an end objective such as symbol error probability (SEP) or capacity.

Contributions: We make the following contributions.

- We systematically develop the optimal AS rule that minimizes the SEP for a MISO secondary system that is subject to an average primary interference constraint. Given a transmit power, we show that the SEP-optimal AS rule is a linear combination of the STx-PRx channel power gain and an exponentially decaying function of the STx-SRx gain. The optimal selection rule is, thus, non-linear in nature.
- We also present a simpler variant of the optimal rule called the *upper bound-based optimal rule* that minimizes a tight Chernoff upper bound of the SEP instead. Its appeal lies in its integral-free closed form. We also show through our results that the SEPs of the SEP-optimal rule and the upper bound-based optimal rule are indistinguishable from each other.
- Another utility of the upper bound-based optimal rule is that its SEP analysis is tractable, unlike that of the exact rule. We derive its exact SEP and an SEP upper bound for the general case with L transmit antennas at STx. We also show that the analytical expressions simplify further when the STx has $L = 2$ antennas. A key challenge that the analysis tackles is the non-linear form of the selection rule, which is unlike the linear selection rules that have been considered in the literature on single transmit AS [11], [22].
- An insightful asymptotic characterization of the upper bound-based optimal rule is also developed. It shows that an error floor occurs due to the average primary interference constraint, and that the error floor is an exponentially decreasing function of the number of transmit antennas.
- Extensive simulation results are presented to study the performance of the upper bound-based optimal AS rule and benchmark its performance with many rules that have been proposed in the literature. In order to provide as fair a comparison as possible, we compare against enhanced versions of the MI and MSLIR rules that always adhere to the average interference constraint. This is achieved by allowing an extra zero-transmit power option at the STx. Intuitively, the latter option is beneficial when all the STx-PRx channel power gains are large, which makes the secondary transmissions interfere considerably with the primary.
- Finally, new analytical results for the SEPs of the enhanced MI and MSLIR rules are also developed. Hitherto, the MI and MSLIR rules had only been studied using simulations. These results lead to new insights about the optimality of the ad hoc rules and bring out new interrelationships among them. For example, we show that the upper bound-based optimal rule, enhanced MI rule, and the DS rule are equivalent only for large values of transmit power, and that the enhanced MSLIR rule is suboptimal in most scenarios.

The paper is organized as follows. Section II develops the system model and the problem statement. The optimal selection rule and SEP analysis are in Section III. Section IV analyzes the benchmark selection rules. Numerical results in Section V are followed by our conclusions in Section VI. Several mathematical derivations are relegated to the Appendix.

II. System Model and Problem Statement

We use the following notation henceforth. The absolute value of a complex number x is denoted by $|x|$. The probability of an event A and the conditional probability of A given B are denoted by $\Pr(A)$ and $\Pr(A|B)$, respectively. For a random variable (RV) X, $f_X(x)$ denotes its probability density function (PDF) and $\mathbf{E}_X[\cdot]$ denotes it expectation. Scalar variables are written in normal font and vector variables are written in bold font. $I_{\{a\}}$ denotes the indicator function; it is 1 if a is true and is 0 otherwise.

As shown in Figure 1, we consider an underlay CR system in which an STx transmits data to an SRx; its transmissions cause interference at a PRx. The SRx and the STx constitute the secondary system. The PRx and the SRx have one receive antenna each. The STx has L transmit antennas and one RF chain; it, therefore, needs to select one of its antennas for transmission. For $i \in \{1, 2, \ldots, L\}$, h_i denotes the instantaneous channel power gain between the i^{th} antenna of the STx and the SRx antenna, and g_i denotes the instantaneous channel power gain between the i^{th} antenna of the STx and the PRx antenna. We assume Rayleigh fading. The STx-SRx channels are assumed to be independent and identically distributed (i.i.d.) random variables (RVs), and so are the STx-PRx channels. This assumption is justified when the antennas at the STx are spaced sufficiently apart in a rich scattering environment. Thus, the channel power gains h_i and g_i are i.i.d. exponential RVs with means μ_h and μ_g, respectively. Let $\mathbf{h} \triangleq [h_1, h_2, \ldots, h_L]$ and $\mathbf{g} \triangleq [g_1, g_2, \ldots, g_L]$.

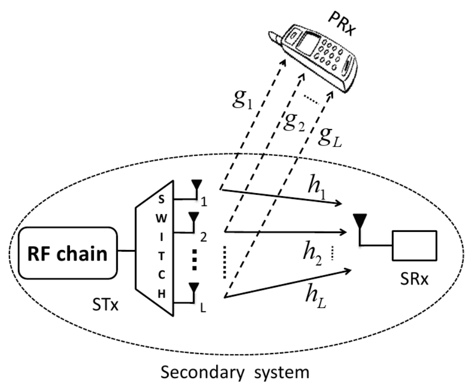

Fig. 1. System model with one PRx and a secondary system consisting of an STx with L transmit antennas and one RF chain that communicates with an SRx with one receive antenna.

A. Selection Options and Data Transmission

The STx transmits a symbol x that is drawn with equal probability from an M-ary phase shift keying (MPSK) constellation. It can transmit using one of the L antennas with fixed symbol energy E_t. Transmission using Antenna i is represented by option i, for $i = 1, \dots, L$. Further, it may decide to transmit with zero power in order to not interfere with the primary. We shall represent the zero-transmit power option by 0 and shall define the corresponding channel power gains as zero, i.e., $h_0 \triangleq 0$ and $g_0 \triangleq 0$. When the STx uses the zero-transmit power option, the SEP is $m \triangleq 1 - \frac{1}{M}$, since the optimal receiver in this case just chooses any one of the M symbols as its decoded symbol with equal probability [23].

Let $s \in \{0, 1, \dots, L\}$ be the option selected. The signal r received by the SRx and the interference signal i_p seen by the PRx are given by

$$r = \sqrt{E_t}\sqrt{h_s}e^{j\theta_{h_s}}x + n + w_{ps}, \quad (1)$$

$$i_p = \sqrt{E_t}\sqrt{g_s}e^{j\theta_{g_s}}x, \quad (2)$$

where $|x|^2 = 1$, θ_{h_s} and θ_{g_s} are the phases of the complex baseband STx-SRx and STx-PRx channel gains, respectively, and n is circular symmetric complex additive white Gaussian noise at the SRx. The interference seen by the SRx due to primary transmissions is w_{ps}, and is assumed to be Gaussian. This corresponds to a worst case model for the interference and makes the problem of finding the optimal AS rule tractable. Therefore, $n + w_{ps}$ is a circular symmetric complex Gaussian RV, whose variance is denoted by σ^2.

We assume that the STx knows $\mathbf{h}$ and $\mathbf{g}$, i.e., its channel power gains to the SRx and to the PRx. This has also been assumed in the literature on AS in CR, e.g., [17], [18], [20]. Note also that no knowledge of the phases of any complex baseband channel gains is required at the STx.[1] The SRx uses a coherent receiver, and is assumed to know h_s and θ_{h_s}.[2] No knowledge of $\mathbf{g}$ or the channel gains of any other antenna is required at the SRx.

[1]In the time division duplex (TDD) mode of operation, information about $\mathbf{h}$ and $\mathbf{g}$ can be obtained by the STx by exploiting reciprocity. The STx uses the signals it receives from the SRx and PRx when they transmit in order to estimate $\mathbf{h}$ and $\mathbf{g}$. Since phase information is not required, simple signal strength-based techniques can be used for estimation. We note that these results also serve as bounds on the performance of AS in CR systems that have access to either partial or imperfect knowledge of $\mathbf{g}$.

B. Problem Statement

Terminology: A selection rule ϕ is a mapping $\phi : (\mathbb{R}^+)^L \times (\mathbb{R}^+)^L \to \{0, 1, \dots, L\}$ that selects one of the $L + 1$ options for every realization of $\mathbf{h}$ and $\mathbf{g}$. We define a *feasible selection rule* to be a rule whose average interference is less than or equal to I_{ave}. Let $\mathcal{Z}$ be the set of all feasible selection rules.

Our goal is to find the optimal transmit AS rule ϕ^*, which minimizes the average SEP of the secondary system while ensuring that the average interference caused to the PRx is below a threshold I_{ave}. We first consider the case where E_t is given. The optimization of E_t is handled in Section V. Let SEP(h_s) denote the instantaneous SEP given channel power gain h_s of the selected option s. Using (2), the average interference caused to the PRx is given by $E_t \mathbf{E}_{\mathbf{h},\mathbf{g}}[g_s]$.

Our problem can be mathematically stated as follows:

$$\begin{aligned} \min_{\phi} \quad & \mathbf{E}_{\mathbf{h},\mathbf{g}}[\text{SEP}(h_s)] \\ \text{subject to} \quad & E_t \mathbf{E}_{\mathbf{h},\mathbf{g}}[g_s] \le I_{\text{ave}}, \\ & s = \phi(\mathbf{h}, \mathbf{g}). \end{aligned} \quad (3)$$

III. Optimal Antenna Selection Rule and SEP Analysis

We now derive the optimal selection rule. We then analyze its SEP.

A. Optimal Selection Rule

Let us first consider the selection rule that minimizes the SEP at the SRx when the average interference constraint in (3) is not active. Clearly, in this case, the optimal rule is the unconstrained rule, which selects the antenna with the highest channel power gain from the STx to the SRx. It is given by $s = \arg\max_{i \in \{1,\dots,L\}} \{h_i\}$. Therefore, the average interference caused to the PRx by the unconstrained rule, I_{un}, is $I_{\text{un}} = E_t \mathbf{E}_{\mathbf{h},\mathbf{g}}[g_s] = E_t \mu_g$. The second equality follows because the unconstrained rule does not take into account the STx-PRx channel power gain.

However, when $I_{\text{un}} > I_{\text{ave}}$, the unconstrained AS rule is not a feasible rule. Therefore, it cannot be optimal. The following result completely characterizes the optimal AS rule.

Theorem *1:* The optimal selection rule ϕ^*, where $s^* = \phi^*(\mathbf{h}, \mathbf{g})$, that minimizes the SEP under the average interference constraint is as follows:

$$s^* = \begin{cases} \arg\max_{i \in \{1,\dots,L\}} \{h_i\}, & I_{\text{un}} \le I_{\text{ave}} \\ \arg\min_{i \in \{0,1,\dots,L\}} \{\text{SEP}(h_i) + \lambda g_i\}, & I_{\text{un}} > I_{\text{ave}}. \end{cases} \quad (4)$$

When $I_{\text{un}} > I_{\text{ave}}$, we have $\lambda > 0$. The value of λ is such that the STx satisfies the average interference constraint with equality, i.e., $E_t \mathbf{E}_{\mathbf{h},\mathbf{g}}[g_{s^*}] = I_{\text{ave}}$.

Proof: The proof is given in Appendix A. ■

[2]In practice this can be achieved by embedding a pilot along with the data symbols once in every coherence interval, since the channel does not change within a coherence interval.

The parameter λ is computed numerically, as is typical of several optimization problems in wireless communications that are subject to an average constraint, e.g., optimal link adaptation [24] and water-filling in time, space, or frequency [25].

The SEP as a function of h_s for MPSK is given by [26, (40)]

$$\text{SEP}(h_s) = \frac{1}{\pi}\int_0^{m\pi} \exp\left(\frac{-h_s E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2 \sin^2\theta}\right) d\theta, \quad (5)$$

where, as mentioned, $m = 1 - \frac{1}{M}$. Substituting (5) in (4) we see that the SEP-optimal AS rule is a non-linear function of h_i. This is unlike the MI, MSLIR, and the DS rules.

B. Simpler Upper Bound-based Optimal Rule

Since the rule in (4) is in the form of a single integral, it is desirable to simplify it. This is achieved by instead minimizing the Chernoff upper bound of the SEP, as we show below.

The upper bound on the SEP of MPSK is given by

$$\text{SEP}(h_s) \le m \exp\left(\frac{-h_s E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2}\right). \quad (6)$$

The optimization problem that minimizes the above bound can be written as

$$\begin{aligned} \min_{\phi} \quad & m\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\exp\left(\frac{-h_s E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2}\right)\right] \\ \text{subject to} \quad & E_t \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_s\right] \le I_{\text{ave}}, \\ & s = \phi(\mathbf{h}, \mathbf{g}). \end{aligned} \quad (7)$$

Along lines of Appendix A, it can be shown that the optimal rule, which we shall refer to as the *upper bound-based optimal rule*, is given by

$$s^* = \begin{cases} \arg\max_{i\in\{1,\ldots,L\}} \{h_i\}, & I_{\text{un}} \le I_{\text{ave}} \\ \arg\min_{i\in\{0,1,\ldots,L\}} \{y_i + \lambda g_i\}, & I_{\text{un}} > I_{\text{ave}} \end{cases}, \quad (8)$$

where

$$y_i \triangleq m \exp\left(\frac{-h_i E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2}\right), \quad i \in \{0, 1, \ldots, L\}. \quad (9)$$

Note that $\lambda = 0$ makes the rules in (4) and (8) equivalent to the unconstrained rule, whose SEP is given in [13, (36)] .

C. SEP Analysis

1) General Case of L Transmit Antennas: We now analyze the SEP of the upper bound-based rule in (8) when $\lambda > 0$. The average SEP for L transmit antennas is denoted by $\text{SEP}^{(L)}$.

Theorem *2:* The average SEP of the secondary system for the upper bound-based optimal rule is given by

$$\begin{aligned} \text{SEP}^{(L)} = {} & m\left(\frac{\alpha e^{-\frac{m}{\lambda\mu_g}}(\lambda\mu_g)^{\frac{\alpha}{\Omega}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}, \frac{m}{\lambda\mu_g}\right)\right)^L \\ & + \frac{L\alpha}{\pi\Omega m^{\frac{\alpha}{\Omega}}\mu_g}\int_0^{m\pi}\int_0^m\int_0^{\frac{m-y_1}{\lambda}} \left(\frac{y_1}{m}\right)^{\csc^2(\theta)} y_1^{\frac{\alpha}{\Omega}-1} e^{\frac{-g_1}{\mu_g}} \\ & \times\left(1 - e^{-\frac{y_1+\lambda g_1}{\lambda\mu_g}}\left(\frac{\lambda\mu_g}{m}\right)^{\frac{\alpha}{\Omega}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}+1, \frac{y_1+\lambda g_1}{\lambda\mu_g}\right)\right)^{L-1} dg_1 dy_1 d\theta, \end{aligned} \quad (10)$$

where $\alpha \triangleq \csc^2(\frac{\pi}{M})$, $\Omega \triangleq \frac{E_t\mu_h}{\sigma^2}$, and $\widetilde{\gamma}(s,x) \triangleq \int_0^x t^{s-1} e^t \, dt$.

Proof: The proof is given in Appendix B. ■

Note that $\widetilde{\gamma}(\cdot,\cdot)$ is a modified version of the lower incomplete gamma function [27, (8.350.1)], and can be evaluated using standard routines available for the latter. The SEP expression in (10) is in the form of a triple integral. It is a function of Ω and λ, which depends on I_{ave}/E_t. The second term in (10) can be simplified further by using the inequality $\sin^2(\theta) \le 1$ to get the following upper bound $\text{SEP}_{UB}^{(L)}$:

$$\begin{aligned} \text{SEP}^{(L)} \le \text{SEP}_{UB}^{(L)} = {} & \frac{L\alpha}{\Omega m^{\frac{\alpha}{\Omega}}\mu_g}\int_0^m\int_0^{\frac{m-y_1}{\lambda}} y_1^{\frac{\alpha}{\Omega}} e^{\frac{-g_1}{\mu_g}} \\ & \times\left(1 - e^{-\frac{y_1+\lambda g_1}{\lambda\mu_g}}\left(\frac{\lambda\mu_g}{m}\right)^{\frac{\alpha}{\Omega}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}+1, \frac{y_1+\lambda g_1}{\lambda\mu_g}\right)\right)^{L-1} dg_1\, dy_1 \\ & + m\left(\frac{\alpha e^{-\frac{m}{\lambda\mu_g}}(\lambda\mu_g)^{\frac{\alpha}{\Omega}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}, \frac{m}{\lambda\mu_g}\right)\right)^L. \end{aligned} \quad (11)$$

Given the non-linear nature of the optimal selection rule, further simplifications are not possible to the best of our knowledge. The double integral above is evaluated numerically. Note that even this result is a significant improvement compared to Monte Carlo simulations.

In a similar manner, the average interference I_{opt} caused to the PRx when the upper bound-based optimal rule in (8) is used can be shown to be equal to

$$\begin{aligned} I_{\text{opt}} = {} & \frac{E_t L\alpha}{\Omega m^{\frac{\alpha}{\Omega}}\mu_g}\int_0^m\int_0^{\frac{m-y_1}{\lambda}} g_1 y_1^{\frac{\alpha}{\Omega}-1} e^{\frac{-g_1}{\mu_g}} \\ & \times\left(1 - e^{-\frac{y_1+\lambda g_1}{\lambda\mu_g}}\left(\frac{\lambda\mu_g}{m}\right)^{\frac{\alpha}{\Omega}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}+1, \frac{y_1+\lambda g_1}{\lambda\mu_g}\right)\right)^{L-1} dg_1 dy_1. \end{aligned}$$

This result is useful in numerically determining λ when it is non-zero, as it is the solution of the equation $I_{\text{opt}} = I_{\text{ave}}$.

Approximate SEP Analysis: To derive the upper bound in (11), we used the Chernoff bound. Very similar expressions also arise when the integral-free SEP approximations for MPSK that were proposed in [24] are used instead of the exact SEP expression. These are also motivated by the Chernoff bound. The only difference lies in the constants.

2) $L = 2$ Transmit Antennas: We now investigate the special case of an STx with two transmit antennas, and show that the SEP expressions simplify further.

Corollary *1:* The average SEP of the secondary system for the upper bound-based optimal rule for $L = 2$ transmit antennas is given by

$$\begin{aligned} \text{SEP}^{(2)} = {} & m\left(\frac{\alpha(\lambda\mu_g)^{\frac{\alpha}{\Omega}} e^{\frac{-m}{\lambda\mu_g}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}, \frac{m}{\lambda\mu_g}\right)\right)^2 + \left(\frac{\alpha}{\Omega m^{\frac{\alpha}{\Omega}}}\right)^2 \\ & \times \frac{(\lambda\mu_g)^{\frac{\alpha}{\Omega}}}{\pi}\int_0^{m\pi}\int_0^m \left[e^{\frac{-y_1}{\lambda\mu_g}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}, \frac{y_1}{\lambda\mu_g}\right) - e^{\frac{y_1-2m}{\lambda\mu_g}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}, \frac{m}{\lambda\mu_g}\right)\right. \\ & \left. + e^{\frac{y_1}{\lambda\mu_g}}\left(\gamma\left(\frac{\alpha}{\Omega}, \frac{y_1}{\lambda\mu_g}\right) - \gamma\left(\frac{\alpha}{\Omega}, \frac{m}{\lambda\mu_g}\right)\right)\right]\left(\frac{y_1}{m}\right)^{\csc^2(\theta)} y_1^{\frac{\alpha}{\Omega}-1} dy_1 d\theta \\ & + \frac{1}{\pi}\int_0^{m\pi}\frac{2\alpha^2\sin^4(\theta)}{\left(\Omega + \alpha\sin^2(\theta)\right)\left(\Omega + 2\alpha\sin^2(\theta)\right)} d\theta. \end{aligned} \quad (12)$$

Proof: The proof is given in Appendix C. ■

The expression in (12) is in the form of a simpler double integral, unlike the expression for the general case L transmit antennas. The Chernoff upper bound for $\text{SEP}^{(2)}$, which is denoted by $\text{SEP}_{UB}^{(2)}$, will be in the form of a single integral. Using Gauss-Legendre quadrature [28], $\text{SEP}_{UB}^{(2)}$ can be evaluated accurately as a sum of a few terms as follows:

$$\begin{aligned}\text{SEP}_{UB}^{(2)} =& m\left(\left(\frac{\alpha e^{-\frac{m}{\lambda\mu_g}}\left(\lambda\mu_g\right)^{\frac{\alpha}{\Omega}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right)\right)\right)^2 + \frac{m}{2}\left(\frac{\alpha}{\Omega m^{\frac{\alpha}{\Omega}}}\right)^2 \\ &\times\left(\lambda\mu_g\right)^{\frac{\alpha}{\Omega}}\left[\sum_{k=1}^{N} w_k z_k^{\frac{\alpha}{\Omega}}\left(e^{\frac{z_k}{\lambda\mu_g}}\gamma\left(\frac{\alpha}{\Omega},\frac{z_k}{\lambda\mu_g}\right) + e^{\frac{-z_k}{\lambda\mu_g}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega},\frac{z_k}{\lambda\mu_g}\right)\right)\right] \\ &-\left(\frac{\alpha}{\Omega m^{\frac{\alpha}{\Omega}}}\right)^2\left(\lambda\mu_g\right)^{1+\frac{2\alpha}{\Omega}}\widetilde{\gamma}\left(1+\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right)\left[\gamma\left(\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right)\right. \\ &\left. + e^{\frac{-2m}{\lambda\mu_g}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right)\right] + \frac{2m\alpha^2}{\left(\Omega+\alpha\right)\left(\Omega+2\alpha\right)}, \quad (13)\end{aligned}$$

where $z_k \triangleq \frac{m}{2}(x_k+1)$ and x_k and w_k are the N Gauss-Legendre abscissas and weights, respectively. As N increases, the approximation becomes tighter. We have found that $N = 3$ terms are sufficient for $\lambda \geq 0.20$ and $N = 5$ terms are sufficient for $0.05 < \lambda < 0.20$. For $\lambda \leq 0.05$ more terms are required.

D. Asymptotic Behavior of the Selection Rule

Now we analyze the regime in which E_t is large in order to gain further insights about the performance of optimal selection. As E_t increases, $\text{SEP}(h_i)$, for $i \in \{1,\ldots,L\}$, becomes negligible compared to λg_i. Hence, the SEP due to the zero-transmit power option, which is m, becomes the dominant contributor to the SEP. In this case, the optimal rule in (4) for $\lambda > 0$ can be shown to reduce to

$$s^* = \begin{cases} 0, & \text{if } g_1 \geq \frac{m}{\lambda},\ldots,g_L \geq \frac{m}{\lambda} \\ \arg\min_{i\in\{1,\ldots,L\}}\{g_i\}, & \text{otherwise}\end{cases}. \quad (14)$$

From (14), we get probability of $s = 0$ as $\Pr(s=0) = \Pr\left(g_1 \geq \frac{m}{\lambda},\ldots,g_L \geq \frac{m}{\lambda}\right) = \left(e^{-\frac{m}{\lambda\mu_g}}\right)^L$. Thus, the SEP in the asymptotic regime, which we denote by $\text{SEP}_{\text{asym}}^{(L)}$, is simply

$$\text{SEP}_{\text{asym}}^{(L)} \triangleq \lim_{E_t\to\infty}\text{SEP}^{(L)} = me^{-\frac{Lm}{\lambda\mu_g}}. \quad (15)$$

We, thus, see that an error floor occurs when the interference constraint is active. As expected, the error floor increases as λ increases, which corresponds to a tighter interference constraint. However, it decreases exponentially when the number of transmit antennas L increases.

IV. Benchmark Selection Rules

We now state the MI, MSLIR, and DS rules, which have been proposed in the literature. We shall enhance the MI and MSLIR rules in order to make them feasible for all interference threshold values so that a fair performance comparison becomes possible. We then analyze these enhanced rules.

A. MI Rule

The MI rule proposed in [17] always selects the transmit antenna with the smallest channel power gain to the PRx. It is given by

$$s_{\text{mi}} = \arg\min_{i\in\{1,\ldots,L\}}\{g_i\}. \quad (16)$$

Let I_{mi} denote the average interference caused by the MI rule to the primary. Thus, if $I_{\text{mi}} > I_{\text{ave}}$, the MI rule above is infeasible even though its goal is to minimize the interference caused to the primary.

To overcome this we introduce the zero-transmit power option in the MI rule; the STx transmits with zero power in case all the channel power gains to the PRx exceed a threshold τ. Thus, the enhanced MI (EMI) rule that we use is given by

$$s_{\text{emi}} = \begin{cases} 0, & \text{if } g_1 \geq \tau,\ldots,g_L \geq \tau \\ \arg\min_{i\in\{1,\ldots,L\}}\{g_i\}, & \text{otherwise}\end{cases}. \quad (17)$$

The threshold τ is chosen to satisfy the average interference constraint. Clearly, $\tau = \infty$ makes the EMI rule equivalent to the MI rule. Notice also that $\tau = \frac{m}{\lambda}$ corresponds to the asymptotic version of the optimal selection rule in (14). Thus, for large E_t, the optimal selection rule reduces to the EMI rule. We now derive the SEP and average interference of the EMI rule.

Theorem *3:* The SEP of the EMI rule with L transmit antennas is given by

$$\begin{aligned}\text{SEP}^{(L)} &= me^{\frac{-L\tau}{\mu_g}} + \frac{1}{\pi}\left(1-e^{\frac{-L\tau}{\mu_g}}\right) \\ &\times\left(m\pi - \sqrt{\frac{\Omega}{\alpha+\Omega}}\tan^{-1}\left(\sqrt{\frac{\alpha+\Omega}{\Omega}}\tan(m\pi)\right)\right). \quad (18)\end{aligned}$$

Recall that $\alpha = \csc^2(\frac{\pi}{M})$ and $\Omega = \frac{E_t\mu_h}{\sigma^2}$. The average interference I_{emi} caused to the PRx by the EMI rule is

$$I_{\text{emi}} = \frac{E_t\mu_g}{L}\left[1-\left(1+\frac{L\tau}{\mu_g}\right)e^{\frac{-L\tau}{\mu_g}}\right]. \quad (19)$$

Proof: The proof is given in Appendix D. ■

Taking the limit $\tau \to \infty$ in (19) yields $I_{\text{mi}} = \frac{E_t\mu_g}{L}$. Equating (19) with I_{ave} yields the following explicit characterization of τ in terms of I_{ave}:

$$\tau = \frac{\mu_g}{L}\left[-1-W_{-1}\left(\frac{LI_{\text{ave}}}{eE_t\mu_g}-\frac{1}{e}\right)\right], \quad (20)$$

where $W_{-1}(x)$ is the lower branch of the Lambert-W function, which is defined as the inverse of the function $f(x) = xe^x$ [29].

B. MSLIR Rule

The MSLIR rule proposed in [17] selects the antenna with the highest ratio of the STx-SRx and STx-PRx gains. It is given by

$$s_{\text{mslir}} = \arg\max_{i\in\{1,\ldots,L\}}\left\{\frac{h_i}{g_i}\right\}. \quad (21)$$

Let the average interference caused by this rule be denoted by I_{mslir}. Therefore, the MSLIR rule is infeasible if $I_{\text{mslir}} > I_{\text{ave}}$.

As before, we introduce the zero-transmit power option in the rule. The enhanced MSLIR (EMSLIR) rule is then as follows:

$$s_{\text{emslir}} = \begin{cases} 0, & \text{if } \frac{h_1}{g_1} \leq \eta, \ldots, \frac{h_L}{g_L} \leq \eta \\ \arg\max_{i \in \{1,\ldots,L\}} \{\frac{h_i}{g_i}\}, & \text{otherwise} \end{cases}. \quad (22)$$

The threshold η is chosen such that the interference constraint is satisfied with equality, i.e., $E_t \mathbf{E}[g_{s_{\text{emslir}}}] = I_{\text{ave}}$. Note that $\eta = 0$ makes the EMSLIR rule equivalent to the MSLIR rule.

The expressions for the SEP and average interference of the EMSLIR rule are as follows.

Theorem *4:* The average SEP of the EMSLIR rule with L transmit antennas is given by

$$\text{SEP}^{(L)} = m\left(\frac{\eta\mu_g}{\eta\mu_g + \mu_h}\right)^L + \frac{L}{\pi{\mu_h}^L}\int_0^{m\pi}\int_0^{\infty} {h_1}^{L-1} e^{-\left(\frac{h_1 E_t}{\alpha\sigma^2 \sin^2(\theta)}\right)} \times \left(\gamma\left(2-L, \frac{h_1}{\mu_h} + \frac{h_1}{\eta\mu_g}\right) - \gamma\left(2-L, \frac{h_1}{\mu_h}\right)\right) dh_1 d\theta, \quad (23)$$

where $\gamma(\cdot,\cdot)$ is the incomplete gamma function [27]. The average interference I_{emslir} caused to the PRx is equal to

$$I_{\text{emslir}} = \frac{2E_t\mu_g}{L+1}\left(L\left(\frac{\eta\mu_g}{\eta\mu_g + \mu_h}\right)^{L+1} - (L+1)\left(\frac{\eta\mu_g}{\eta\mu_g + \mu_h}\right)^L + 1\right). \quad (24)$$

Proof: The proof is given in Appendix E. ■

Equating (24) with I_{ave} yields η. Substituting $\eta = 0$ in (24) yields $I_{\text{mslir}} = \frac{2E_t\mu_g}{L+1}$. The SEP expression in (23) is in the form of a double integral. Its upper bound can be expressed in a single integral form using $\sin^2(\theta) \leq 1$, and can be computed accurately as a sum of a few terms using Gauss-Laguerre quadrature [28]. The details are omitted.

C. DS Rule

The difference AS rule for $\delta \in [0, 1]$ is given by [18]

$$s_{\text{ds}} = \arg\max_{\{1,\ldots,L\}} \{\delta h_i - (1-\delta) g_i\}. \quad (25)$$

Note that $\delta = 1$ corresponds to the unconstrained selection rule and $\delta = 0$ corresponds to the MI rule in (16). Thus, the DS rule can control the average interference caused to the primary by choosing an appropriate δ. However, the minimum interference caused by the DS rule is the same as that of the MI rule in (16). Therefore, the DS rule is infeasible when $I_{\text{mi}} > I_{\text{ave}}$. Introducing the zero-transmit power option can make it feasible for all I_{ave}. We do not delve into it further due to space constraints. The SEP of this rule is given in [21, (6)] for BPSK, and can be generalized to MPSK. The average interference caused to the primary is given in [18, (22)].

V. Numerical Results and Performance Benchmarking

We now present Monte Carlo simulations that use 10^6 samples to verify our analytical results and benchmark the behavior of the upper bound-based optimal AS rule under different conditions. The mean channel powers and noise variance are set as unity, i.e., $\mu_h = \mu_g = \sigma^2 = 1$.

Figure 2 compares the SEPs of the optimal selection rule in (4) and the upper bound-based optimal rule in (8) as a function of the symbol energy E_t. We see that the two are indistinguishable from each other. This is because the Chernoff bound for the SEP of MPSK is tight. As a result, the same antenna gets selected by the two rules with high probability.

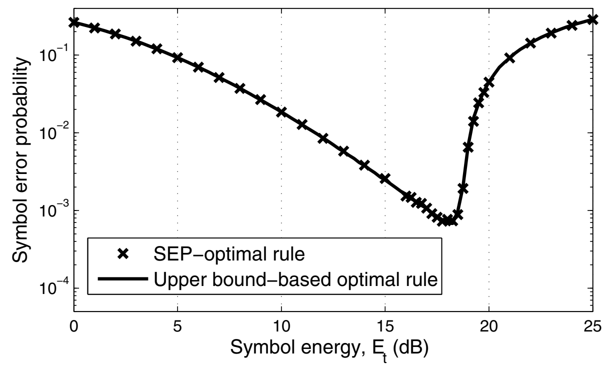

Fig. 2. Comparison of the SEPs of the optimal AS rule in (4) and the upper bound-based optimal rule in (8) ($L = 2$, $M = 4$, and $I_{\text{ave}} = 16$ dB).

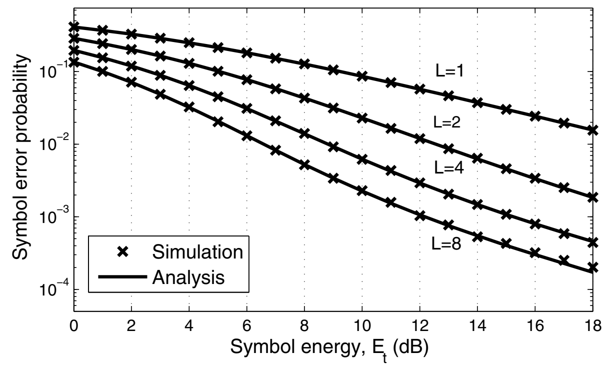

Fig. 3. SEP as a function of E_t of the upper bound-based optimal rule for different numbers of secondary transmit antennas ($\lambda = 0.1$ and $M = 4$).

Figure 3 plots the SEP of the upper bound-based optimal rule as a function of E_t for different numbers of STx antennas with $\lambda = 0.1$. From the average interference constraint in (3), a fixed λ implies that the ratio $\frac{I_{\text{ave}}}{E_t}$ is kept constant on each curve. We observe that the analytical and simulation results match very well. As expected, the SEP decreases significantly as L increases.

Figure 4 studies the SEP of the upper bound-based optimal rule as a function of E_t for $L = 2$ antennas for different values of λ. The $\lambda = 0$ curve corresponds to the scenario where the interference constraint is not active and the unconstrained rule is optimal. As λ increases, the SEP increases due to a tighter average interference constraint. Notice that the analytical and simulation results again match each other very well. We, therefore, no longer distinguish between the two henceforth.

Figure 5 plots the SEP and its upper bound for a larger range of E_t for $\lambda = 0.5$ and different values of L. The figure verifies the result in Section III-D about the occurrence of an error floor occurs at larger E_t. Notice that the error floor drops significantly as L increases. Notice also that the gap between the exact SEP and its upper bound disappears at larger E_t.

Figure 6 plots the SEP as a function of E_t when the average interference threshold is fixed at $I_{\text{ave}} = 10$ dB. We see that

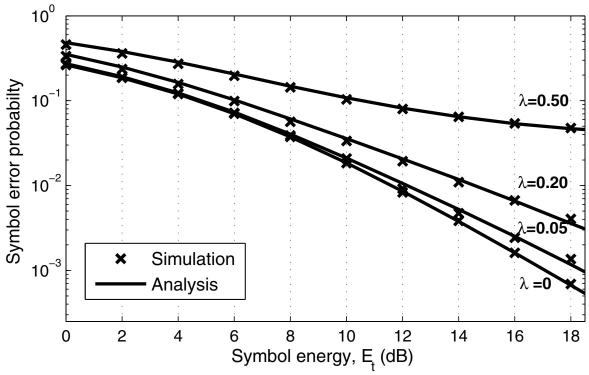

Fig. 4. SEP as a function of E_t of the SEP upper bound-based optimal rule for different values of λ, different values of which correspond to different values for $\frac{I_{\text{ave}}}{E_t}$ ($L = 2$ and $M = 4$).

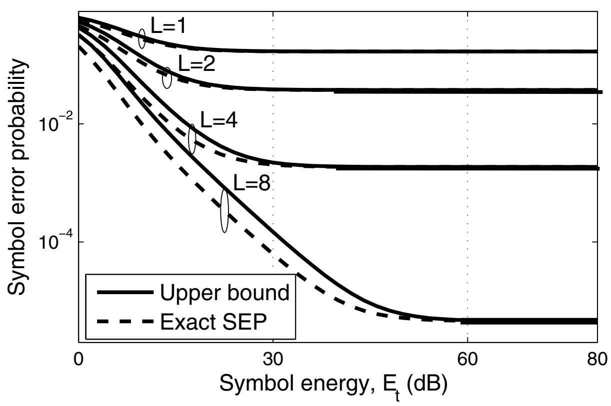

Fig. 5. Large E_t: SEP and its upper bound of the upper bound-based optimal rule as a function of E_t for different number of STx antennas ($\lambda = 0.5$ and $M = 4$).

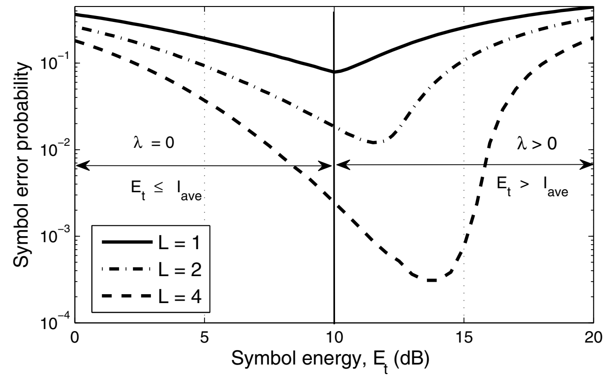

Fig. 6. SEP of the upper bound-based optimal rule as a function of E_t for different numbers of secondary transmit antennas ($I_{\text{ave}} = 10$ dB and $M = 4$).

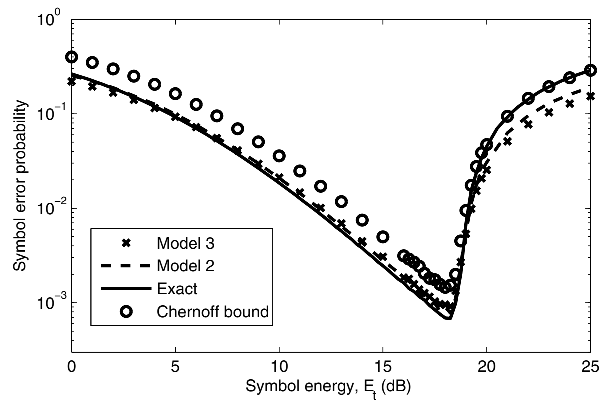

Fig. 7. Comparison of SEPs obtained using the approximate SEP expressions proposed in [24] and the exact SEP and its upper bound derived in (10) and (11), respectively ($L = 2$, $M = 4$, and $I_{\text{ave}} = 16$ dB).

there are three regions of operation of the optimal rule for $L = 2$: (i) $E_t \leq 10$ dB: In this case the interference constraint is not active. Hence, $\lambda = 0$ and the optimal rule selects the antenna with the highest STx-SRx channel power gain. (ii) 10 dB $< E_t \leq 12$ dB: In this case λ becomes non-zero, but is very small. The SEP continues to decrease as E_t increases. (iii) $E_t > 12$ dB: The SEP now increases as E_t increases. This is because the probability that the STx does not transmit increases so as to adhere to the average interference constraint. Thus, $E_t = 12$ dB is the optimal transmit symbol energy when $I_{\text{ave}} = 10$ dB and $L = 2$. Similarly $E_t = 14$ dB is optimal for $L = 4$.[3] The optimal value of E_t is I_{ave} itself when $L = 1$. Thus, the optimal value of E_t increases with L.

Figure 7 plots the SEPs of the optimal rule, the SEP Chernoff upper bound $\text{SEP}_{UB}^{(L)}$ in (11), and the SEPs obtained by using the approximate SEP expressions named Model 2 and Model 3 in [24, (12), (13)]. We see that these approximations track the exact SEP well for smaller values of E_t while the $\text{SEP}_{UB}^{(L)}$ curve matches the exact SEP curve for larger E_t.

Figure 8 plots the SEP as a function of E_t when the average interference threshold I_{ave} is fixed at 12 dB. This is done for different MPSK constellation sizes. As expected, the SEP increases as the constellation size increases. Further, the optimal symbol energy is a function of the constellation size. Figure 9 plots the cumulative distribution function (CDF) of the instantaneous interference seen by the PRx. From this, other performance metrics of interest such as the primary outage probability, which is the probability that the interference at the PRx exceeds a threshold, can be read off.

Performance benchmarking: Figure 10 compares the SEP of the optimal rule with those of the EMI, EMSLIR, and DS rules, for $I_{\text{ave}} = 16$ dB and $L = 2$. For $E_t < I_{\text{ave}} = 16$ dB, the SEP of the optimal rule is the same as that of unconstrained rule and the DS rule ($\delta = 1$). For $E_t \geq 19$ dB, the optimal rule becomes equivalent to the EMI rule (cf. Section IV-A). The DS rule performs worse than the optimal rule when 16 dB $<$ $E_t < 19$ dB, and is infeasible beyond 19 dB. The EMSLIR rule is sub-optimal for all values of E_t. We observe that the minimum SEP of the optimal rule is lower by a factor of 16.5, 3.5, and 2.4 than the minimum SEPs of the EMI, EMSLIR, and DS rules.

VI. Conclusions

We considered the problem of antenna selection at a secondary transmitter that operates under an average interference constraint imposed by the underlay mode of operation of a

[3] It is difficult to analytically characterize the optimal E_t in closed-form because the SEP expression and its bound depend on λ, which itself depends on E_t.

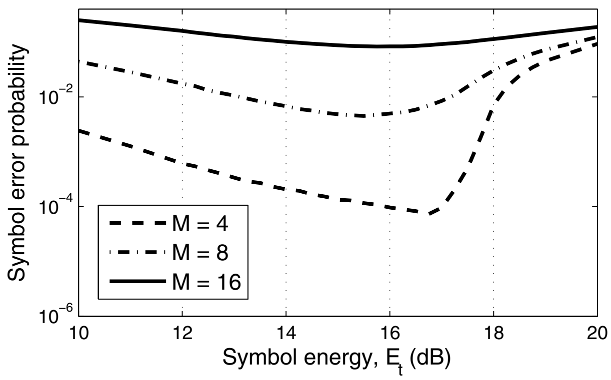

Fig. 8. SEP of the upper bound-based optimal rule as a function of E_t for different constellation sizes ($I_{\text{ave}} = 12$ dB and $L = 4$).

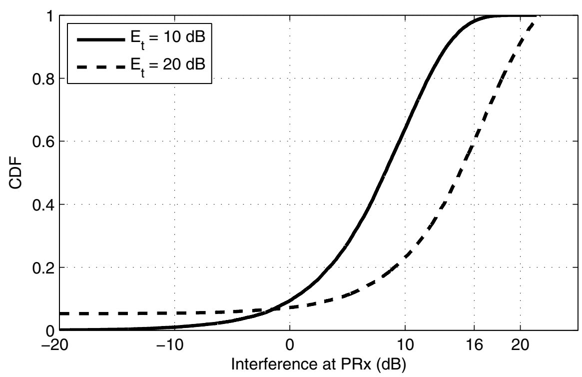

Fig. 9. CDF of interference seen by PRx ($I_{\text{ave}} = 16$ dB, $L = 2$, and $M = 4$).

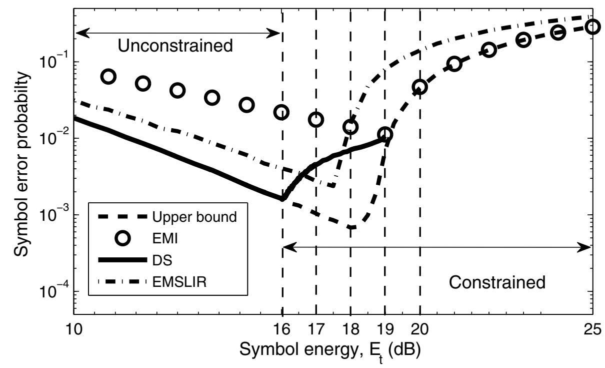

Fig. 10. Comparison of the SEPs of the upper bound-based optimal rule and several benchmark rules ($L = 2$, $M = 4$, and $I_{\text{ave}} = 16$ dB).

cognitive radio. We developed the optimal selection rule that minimizes the SEP, and saw that it is non-linear in nature. It is functionally quite different from the many ad hoc rules that have been proposed in the literature. We then analyzed the SEP of the upper bound-based optimal rule for the general case of L transmit antennas. These expressions simplified further for $L = 2$ antennas. We also analyzed the SEPs of the enhanced MI and MSLIR rules. We saw that the SEPs of the optimal rule and the upper bound-based optimal rule are indistinguishable from each other. The unconstrained rule and the DS rule behave as the optimal rule for small E_t, and the optimal rule becomes equivalent to the EMI rule for larger E_t. While an error floor is unavoidable, it decreases exponentially as L increases.

The analytical techniques presented in this paper open the door to developing optimal subset selection rules when the transmitter has more than one RF chain. Further, it is of interest to investigate the optimal selection rule when the STx is subject to a constraint on the outage probability it causes at the PRx. Another interesting problem is characterizing the joint and optimal power control and antenna selection policy.

Appendix

A. Proof of Theorem 1

When $I_{\text{un}} \leq I_{\text{ave}}$, the unconstrained rule is feasible. Therefore, it must be the SEP-optimal rule. Now, consider the case when $I_{\text{un}} > I_{\text{ave}}$. A selection rule that always chooses the zero-transmit power option causes zero interference to the PRx. It is, therefore, feasible for any I_{ave}. Therefore, the set of all feasible selection rules, $\mathcal{Z}$, is a non-empty set.

Let $\phi \in \mathcal{Z}$ be a feasible rule. For a given $\lambda > 0$, define

$$L_\phi(\lambda) \triangleq \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_s) + \lambda g_s\right], \tag{26}$$

where $s = \phi(\mathbf{h}, \mathbf{g})$. From the definition of ϕ^* for $I_{\text{un}} > I_{\text{ave}}$ in (4) , it follows that $L_{\phi^*}(\lambda) \leq L_\phi(\lambda)$. Therefore,

$$\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_{s^*})\right]+\lambda\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_{s^*}\right] \leq \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_s)\right]+\lambda\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_s\right], \tag{27}$$

where $s^* = \phi^*(\mathbf{h}, \mathbf{g})$. Choose λ such that $\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_{s^*}\right] = \frac{I_{\text{ave}}}{E_t}$. Such a unique choice of λ is possible since $0 \leq I_{\text{ave}} < I_{\text{un}}$ and the average interference decreases monotonically as λ increases. Thus, ϕ^* is also a feasible selection rule. Rearranging the terms in (27), we get

$$\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_{s^*})\right] \leq \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_s)\right] + \lambda\left(\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_s\right] - \frac{I_{\text{ave}}}{E_t}\right). \tag{28}$$

However, since ϕ is a feasible rule, we know that $\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[g_s\right] \leq \frac{I_{\text{ave}}}{E_t}$. Hence, (28) implies that for any feasible antenna selection rule ϕ, $\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_{s^*})\right] \leq \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\text{SEP}(h_s)\right]$. Thus, ϕ^* must be the optimal rule.

B. Proof of Theorem 2

The SEP conditioned on $\mathbf{h}$ and $\mathbf{g}$, which we denote by $\Pr\left(\text{Err}|\mathbf{h}, \mathbf{g}\right)$, can be written as

$$\Pr\left(\text{Err}|\mathbf{h}, \mathbf{g}\right) = \Pr\left(s = 0, \text{Err}|\mathbf{h}, \mathbf{g}\right) + \sum_{i=1}^{L} \Pr\left(s = i, \text{Err}|\mathbf{h}, \mathbf{g}\right).$$

Averaging over $\mathbf{h}$ and $\mathbf{g}$ and using the chain rule, we get the following expression for the SEP:

$$\begin{aligned} \text{SEP}^{(L)} &= \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr\left(s = 0|\mathbf{h}, \mathbf{g}\right)\Pr\left(\text{Err}|\mathbf{h}, \mathbf{g}, s = 0\right)\right] \\ &\quad + \sum_{i=1}^{L} \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr\left(s = i|\mathbf{h}, \mathbf{g}\right)\Pr\left(\text{Err}|\mathbf{h}, \mathbf{g}, s = i\right)\right]. \end{aligned} \tag{29}$$

Using symmetry and the fact that the SEP conditioned on option s depends only on h_s, we get

$$\begin{aligned} \text{SEP}^{(L)} &= \mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr\left(s = 0|\mathbf{h}, \mathbf{g}\right)\Pr\left(\text{Err}|h_0\right)\right] \\ &\quad + L\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr\left(s = 1|\mathbf{h}, \mathbf{g}\right)\Pr\left(\text{Err}|h_1\right)\right]. \end{aligned} \tag{30}$$

Substituting (5) and using the fact that $\Pr(\text{Err}|h_0) = m$, we get

$$\text{SEP}^{(L)} = m\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr(s=0|\mathbf{h},\mathbf{g})\right] + \frac{L}{\pi}\int_0^{m\pi}\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr(s=1|\mathbf{h},\mathbf{g})\exp\left(\frac{-h_1E_t\sin^2\left(\frac{\pi}{M}\right)}{\sigma^2\sin^2\theta}\right)\right]d\theta. \quad (31)$$

From the definition of y_i in (9) and $\mathbf{y} \triangleq [y_1,\ldots,y_L]$, the above expression for the SEP can be recast as

$$\text{SEP}^{(L)} = m\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr(s=0|\mathbf{h},\mathbf{g})\right] + \frac{L}{\pi}\int_0^{m\pi}\mathbf{E}_{\mathbf{y},\mathbf{g}}\left[\Pr(s=1|\mathbf{y},\mathbf{g})\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right]d\theta. \quad (32)$$

From the law of total expectation we know that

$$\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr(s=0|\mathbf{h},\mathbf{g})\right] = \Pr(s=0). \quad (33)$$

Similarly,

$$\mathbf{E}_{\mathbf{y},\mathbf{g}}\left[\Pr(s=1|\mathbf{y},\mathbf{g})\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right] = \mathbf{E}_{y_1,g_1}\left[\Pr(s=1|y_1,g_1)\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right].$$

We evaluate the two terms in (32) separately below.

First term: Recall that the selection rule in (8) is $s^* = \arg\min_{i\in\{0,1,\ldots,L\}}\{y_i+\lambda g_i\}$. Therefore, the first term can be written as

$$m\Pr(s=0) = m\Pr(y_1+\lambda g_1 > m,\ldots,y_L+\lambda g_L > m), = m\left(\Pr(y_1+\lambda g_1 > m)\right)^L. \quad (34)$$

Here, the second equality follows from the independence of the channel power gains of the L antennas. Further, using the PDF of y_1, which is given by $f_{y_1}(y_1) = \frac{\alpha}{\Omega m^{\frac{\alpha}{\Omega}}}y_1^{\frac{\alpha}{\Omega}-1}$, $y_1 \in (0,m]$, we get

$$\Pr(y_1+\lambda g_1 > m) = \int_0^m\int_{\frac{m-y_1}{\lambda}}^{\infty}\frac{e^{-\frac{g_1}{\mu_g}}}{\mu_g}\frac{\alpha y_1^{\frac{\alpha}{\Omega}-1}}{\Omega m^{\frac{\alpha}{\Omega}}}dg_1dy_1 = \int_0^m\frac{\alpha e^{\left(\frac{y_1-m}{\lambda\mu_g}\right)}y_1^{\frac{\alpha}{\Omega}-1}}{\Omega m^{\frac{\alpha}{\Omega}}}dy_1 = \frac{\alpha e^{-\frac{m}{\lambda\mu_g}}(\lambda\mu_g)^{\frac{\alpha}{\Omega}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right).$$

Here, the last equality follows from the definition of $\widetilde{\gamma}(.,.)$ in the theorem statement. Substituting the above equation in (34) completes the evaluation of the first term, which we denote by T_1, and yields

$$T_1 = m\Pr(s=0) = m\left(\frac{\alpha e^{-\frac{m}{\lambda\mu_g}}(\lambda\mu_g)^{\frac{\alpha}{\Omega}}}{\Omega m^{\frac{\alpha}{\Omega}}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega},\frac{m}{\lambda\mu_g}\right)\right)^L. \quad (35)$$

Second term: In a similar manner, from (8), we get

$$\Pr(s=1|y_1,g_1) = \Pr(y_2+\lambda g_2 > y_1+\lambda g_1,\ldots,y_L+\lambda g_L > y_1+\lambda g_1, m > y_1+\lambda g_1|y_1,g_1), = \left(\Pr(y_2+\lambda g_2 > y_1+\lambda g_1, y_1+\lambda g_1 < m|y_1,g_1)\right)^{L-1}. \quad (36)$$

Simplifying $\Pr(y_2+\lambda g_2 > y_1+\lambda g_1, y_1+\lambda g_1 < m|y_1,g_1)$ is similar to simplifying $\Pr(y_1+\lambda g_1 > m)$ in the first term. This yields

$$\Pr(s=1|y_1,g_1) = \left(1-e^{-\frac{y_1+\lambda g_1}{\lambda\mu_g}}\left(\frac{\lambda\mu_g}{m}\right)^{\frac{\alpha}{\Omega}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}+1,\frac{y_1+\lambda g_1}{\lambda\mu_g}\right)\right)^{L-1}I_{\{y_1+\lambda g_1<m\}}.$$

Let the second term of (32) be denoted by T_2. Substituting the above equation in T_2 and changing the integration limits of g_1 to ensure that $y_1+\lambda g_1 < m$, we get

$$T_2 = \frac{L\alpha}{\pi\Omega m^{\frac{\alpha}{\Omega}}\mu_g}\int_0^{m\pi}\int_0^m\int_0^{\frac{m-y_1}{\lambda}}\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}y_1^{\frac{\alpha}{\Omega}-1}e^{\frac{-g_1}{\mu_g}} \times\left(1-e^{-\frac{y_1+\lambda g_1}{\lambda\mu_g}}\left(\frac{\lambda\mu_g}{m}\right)^{\frac{\alpha}{\Omega}}\widetilde{\gamma}\left(\frac{\alpha}{\Omega}+1,\frac{y_1+\lambda g_1}{\lambda\mu_g}\right)\right)^{L-1}dg_1dy_1d\theta.$$

Combining the expressions for T_1 and T_2 gives the desired result in (10).

C. Proof of Corollary 1

Starting from (32) and substituting $L=2$, we get

$$\text{SEP}^{(2)} = m\mathbf{E}_{\mathbf{h},\mathbf{g}}\left[\Pr(s=0|\mathbf{h},\mathbf{g})\right] + \frac{2}{\pi}\int_0^{m\pi}\mathbf{E}_{\mathbf{y},\mathbf{g}}\left[\Pr(s=1|\mathbf{y},\mathbf{g})\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right]d\theta. \quad (37)$$

The first term can be obtained directly from (35). However, the expectation in the second term can be simplified differently. From the law of total expectation, we know that

$$\mathbf{E}_{\mathbf{y},\mathbf{g}}\left[\Pr(s=1|\mathbf{y},\mathbf{g})\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right] = \mathbf{E}_{\mathbf{y}}\left[\Pr(s=1|\mathbf{y})\left(\frac{y_1}{m}\right)^{\csc^2(\theta)}\right]. \quad (38)$$

From (8), we know that

$$\Pr(s=1|\mathbf{y}) = \Pr(y_1+\lambda g_1 < y_2+\lambda g_2, y_1+\lambda g_1 < m|\mathbf{y}).$$

Rearranging the terms and summing over the mutually exclusive events $y_2 < y_1$ and $y_2 > y_1$, we get

$$\Pr(s=1|\mathbf{y}) = \Pr\left(y_2<y_1, g_1-g_2<\frac{y_2-y_1}{\lambda}, g_1<\frac{m-y_1}{\lambda}\,\Big|\,\mathbf{y}\right) + \Pr\left(y_2>y_1, g_1-g_2<\frac{y_2-y_1}{\lambda}, g_1<\frac{m-y_1}{\lambda}\,\Big|\,\mathbf{y}\right).$$

Since g_1 and g_2 are i.i.d. exponential RVs, we can show that

$$\Pr(s=1|\mathbf{y}) = \frac{1}{2}\left(e^{\frac{y_2-y_1}{\lambda\mu_g}} - e^{\frac{y_1+y_2-2m}{\lambda\mu_g}}\right)I_{\{y_2<y_1\}} + \frac{1}{2}\left(2-e^{\frac{y_1-y_2}{\lambda\mu_g}} - e^{\frac{y_1+y_2-2m}{\lambda\mu_g}}\right)I_{\{y_2>y_1\}}.$$

Thus, the expectation in the second term of (37), which we denote by Q, can be written as

$$Q = \frac{1}{2}\Big(\frac{\alpha}{\Omega m^{\frac{\alpha}{\Omega}}}\Big)^2 \int_0^m \Big[\int_0^{y_1}\Big(e^{\frac{y_2-y_1}{\lambda\mu_g}} - e^{\frac{y_1+y_2-2m}{\lambda\mu_g}}\Big) y_2^{\frac{\alpha}{\Omega}-1} dy_2 + \int_{y_1}^m \Big(2 - e^{\frac{y_1-y_2}{\lambda\mu_g}} - e^{\frac{y_1+y_2-2m}{\lambda\mu_g}}\Big) y_2^{\frac{\alpha}{\Omega}-1} dy_2\Big] \times \left(\frac{y_1}{m}\right)^{\csc^2(\theta)} y_1^{\frac{\alpha}{\Omega}-1} dy_1.$$

Simplifying Q in terms of incomplete gamma functions yields the desired result in (12).

D. Proof of Theorem 3

1) SEP Analysis: We start from (31). In the EMI rule, selection of an option s depends only on $\mathbf{g}$. Therefore, the SEP can be written as

$$\text{SEP}^{(L)} = m\mathbf{E}_{\mathbf{g}}\left[\Pr(s=0|\mathbf{g})\right] + \mathbf{E}_{\mathbf{g}}\left[\Pr(s=1|\mathbf{g})\right]\frac{L}{\pi}\int_0^{m\pi} \mathbf{E}_{h_1}\left[\exp\left(\frac{-h_1 E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2 \sin^2\theta}\right)\right] d\theta.$$

Since $\mathbf{E}_{\mathbf{g}}\left[\Pr(s=i|\mathbf{g})\right] = \Pr(s=i)$, for $i \in \{0,1\}$, and h_1 is an exponential RV, we get

$$\text{SEP}^{(L)} = m\Pr(s=0) + \Pr(s=1)\frac{L}{\pi}\int_0^{m\pi} \frac{\sin^2(\theta)}{\sin^2(\theta)+\frac{\alpha}{\Omega}} d\theta. \quad (39)$$

For the EMI rule, $\Pr(s=0) = \Pr(g_1 > \tau, \ldots, g_L > \tau) = \left(\Pr(g_1>\tau)\right)^L = e^{\frac{-L\tau}{\mu_g}}$. By symmetry, the probability of selecting any one of the L antennas is the same. Therefore,

$$\Pr(s=1) = \frac{1-\Pr(s=0)}{L} = \frac{1-e^{\frac{-L\tau}{\mu_g}}}{L}. \quad (40)$$

Substituting $\Pr(s=0)$ and $\Pr(s=1)$ in (39), we get

$$\text{SEP}^{(L)} = m e^{\frac{-L\tau}{\mu_g}} + \frac{1-e^{\frac{-L\tau}{\mu_g}}}{\pi}\int_0^{m\pi}\frac{\sin^2(\theta)}{\sin^2(\theta)+\frac{\alpha}{\Omega}} d\theta. \quad (41)$$

The single integral in the above equation can be simplified by using [27, (2.562)], and leads to the desired result.

2) Average Interference Analysis: The average interference caused to the PRx when we employ the EMI rule is given by

$$I_{\text{emi}} = E_t \sum_{i=1}^{L} \mathbf{E}_{\mathbf{g}}\left[g_i \Pr(s=i|\mathbf{g})\right],$$
$$= E_t L \mathbf{E}_{\mathbf{g}}\left[g_1 \Pr(s=1|\mathbf{g})\right], \quad (42)$$
$$= E_t L \mathbf{E}_{g_1}\left[g_1 \Pr(s=1|g_1)\right]. \quad (43)$$

Here, (42) follows from symmetry, and (43) follows from the law of total expectation. Hence,

$$I_{\text{emi}} = \frac{E_t L}{\mu_g}\int_0^\infty g_1 \Pr(s=1|g_1)\, e^{-\frac{g_1}{\mu_g}} dg_1. \quad (44)$$

For the EMI rule, Antenna 1 is chosen if $g_2 > g_1, \ldots, g_L > g_1$ and $g_1 < \tau$. Hence,

$$\Pr(s=1|g_1) = \Pr(g_2 > g_1, \ldots, g_L > g_1, g_1 < \tau | g_1),$$
$$= \left(\Pr(g_2 > g_1|g_1)\right)^{L-1} I_{\{g_1<\tau\}}. \quad (45)$$

Using the result $\Pr(g_2 > g_1|g_1) = e^{-\frac{g_1}{\mu_g}}$ and simplifying further yields (19).

E. Proof of Theorem 4

1) SEP Analysis: Starting from (31) and proceeding along lines similar to Appendix B, we get

$$\text{SEP}^{(L)} = m\Pr(s=0) + \frac{L}{\pi}\int_0^{m\pi} \mathbf{E}_{h_1,g_1}\left[\Pr(s=1|h_1,g_1)\exp\left(\frac{-h_1 E_t \sin^2\left(\frac{\pi}{M}\right)}{\sigma^2\sin^2\theta}\right)\right] d\theta.$$

The EMSLIR rule selects the zero-transmit power option when $\frac{h_1}{g_1} < \eta, \ldots, \frac{h_L}{g_L} < \eta$. Thus, we have $\Pr(s=0) = \Pr\left(\frac{h_1}{g_1} < \eta, \ldots, \frac{h_L}{g_L} < \eta\right) = \Pr\left(\frac{h_1}{g_1} < \eta\right)^L$. Furthermore,

$$\Pr\left(\frac{h_1}{g_1} < \eta\right) = \int_0^\infty \Pr(h_1 < \eta g_1 | g_1)\frac{e^{-\frac{g_1}{\mu_g}}}{\mu_g} dg_1,$$
$$= \int_0^\infty \left(1 - e^{-\frac{\eta g_1}{\mu_h}}\right)\frac{e^{-\frac{g_1}{\mu_g}}}{\mu_g} dg_1 = \frac{\eta\mu_g}{\eta\mu_g+\mu_h}. \quad (46)$$

Similarly, Antenna 1 is selected when $\frac{h_2}{g_2} < \frac{h_1}{g_1}, \ldots, \frac{h_L}{g_L} < \frac{h_1}{g_1}$ and $\frac{h_1}{g_1} > \eta$. Thus,

$$\Pr(s=1|h_1,g_1) = \Pr\left(\frac{h_2}{g_2} < \frac{h_1}{g_1}, \ldots, \frac{h_L}{g_L} < \frac{h_1}{g_1}, \frac{h_1}{g_1} > \eta \,\Big|\, h_1, g_1\right). \quad (47)$$

Conditioned on h_1 and g_1, the events $\left\{\frac{h_i}{g_i} < \frac{h_1}{g_1}\right\}$, for $i \in \{2,\ldots,L\}$, and $\frac{h_1}{g_1} > \eta$ are mutually independent. Further the RVs $\frac{h_2}{g_2}, \ldots, \frac{h_L}{g_L}$ are identically distributed. Thus,

$$\Pr(s=1|h_1,g_1) = \Pr\left(\frac{h_2}{g_2} < \frac{h_1}{g_1} \,\Big|\, h_1, g_1\right)^{L-1} I_{\left\{\frac{h_1}{g_1}>\eta\right\}}. \quad (48)$$

Using (46), we get $\Pr\left(\frac{h_2}{g_2} < \frac{h_1}{g_1}|h_1,g_1\right) = \frac{\mu_g h_1}{\mu_h g_1 + \mu_g h_1}$. Hence,

$$\text{SEP}^{(L)} = \frac{L}{\pi}\int_0^{m\pi}\int_0^\infty\int_0^{\frac{h_1}{\eta}} \exp\left(\frac{-h_1 E_t\sin^2\left(\frac{\pi}{M}\right)}{\sigma^2\sin^2\theta}\right)\frac{e^{-\frac{g_1}{\mu_g}}}{\mu_g}\frac{e^{-\frac{h_1}{\mu_h}}}{\mu_h} \times \left(\frac{\mu_g h_1}{\mu_h g_1 + \mu_g h_1}\right)^{L-1} dg_1 dh_1 d\theta + m\left(\frac{\eta\mu_g}{\eta\mu_g+\mu_h}\right)^L. \quad (49)$$

Using the variable substitution $q = \frac{g_1}{\mu_g} + \frac{h_1}{\mu_h}$ and simplifying further yields (23).

2) Average Interference Analysis: Carrying out the same steps as in (43) we get

$$I_{\text{emslir}} = E_t L \mathbf{E}_{h_1,g_1}\left[g_1\Pr(s=1|h_1,g_1)\right]. \quad (50)$$

Substituting the expression for $\Pr(s=1|h_1,g_1)$ from (48) and simplifying further yields the desired result in (24).

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