Spectral Efficiency and Energy Efficiency Optimization via Mode Selection for Spatial Modulation in MIMO Systems

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Abstract—**In this work we consider the multiple-input multiple-output system employing spatial modulation based transmission in Rayleigh fading channels with known slow-varying large-scale fading loss and channel correlations. Observing the system performance is affected by transmission mechanisms and configurations, we propose a framework enabling the selection of the transmission mode for the optimal spectral efficiency (SE) or energy efficiency (EE) while conforming to transmission and error rate requirements with low complexity. In the framework, a closed-form error rate approximation is proposed. It renders the formulated SE and EE-based selection problems solvable via naive exhaustive search method. Besides, we propose to reduce the complexity via using look-up tables. Computer simulations are provided to evaluate the framework.**

Index Terms—**Spatial modulation, transmission mode selection, energy efficiency, spectral efficiency, BER.**

I. Introduction

Spatial modulation (SM) based transmission schemes in multiple-input multiple-output (MIMO) systems utilize both the signal and spatial constellations, i.e., both the conventional amplitude and phase modulation (APM) and the antenna indices, to convey information bits [1]–[3]. The distinct feature of SM-based MIMO enhances the utilization of spatial degrees of freedom (DoFs) with limited number of radio frequency (RF) chains, and renders the SM-based MIMO transceiver lower complexity and potentially higher energy efficiency (EE) as compared to the conventional MIMO [3]–[5].

To improve the SM-based MIMO, adaptive designs [3], [6] have been investigated. Here we consider the link adaptive design in which the system adaptively adopts the most suitable transmission scheme and configuration [7]–[13]. To improve the error rate, approaches in [7] and [8] were proposed to adaptively adjust the construction of the signal constellation. To maximize spectral efficiency (SE) with given symbol/bit error rate (SER/BER), [9], [10] were proposed via adapting modulation orders. As considering energy efficiency (EE) maximization, adaptive modulation designs in [11], [12] were proposed without involving circuit power consumption. Moreover, with circuit power included, [13] optimized EE by switching between the SM-MIMO and conventional MIMO transmission. By our survey, most existing works consider only typical SM-MIMO systems. Besides, there is no existing work focusing on the link adaptive design involving both the SM and its different variants, such as the generalized SM (GSM). Notice that, while one merit of those variants is to provide good trade-offs between SE and EE with different numbers of active RF chains, the link adaptive design involving different variants can provide benefits to the systems.

In this work, we propose the framework for selecting the best transmission mode according to the large-scale fading loss and spatial correlations in Rayleigh fading channels. Our goal is to pursue the optimization of two fundamental performance metrics: SE and EE. The framework considers SM-based schemes with different transmission rates, space-signal constellations, numbers of activated antennas, and without transmit diversity design. We first derive the simplified closed-form approximation of the SER/BER applicable for different modes. Then given a pre-determined candidate set of transmission modes, we propose the SE and EE based selection optimization problems for selecting the mode with the best SE and EE, respectively. Both optimization problems are subject to certain error rate, transmission rate, and power constraints. By linking the error rate requirement to the transmit power via the closed-form approximation, the proposed SE and EE optimization problems can be easily solvable by naive exhaustive search with low complexity. Furthermore, since the costly metric computation of the closed-form expression can be replaced by the inexpensive table look-up operation, the complexity of the framework can be further reduced. Throughout the paper we provide simulations to evaluate the proposed framework.

Remark: compared to [14], [15], our SER/BER approximation provides a more simplified closed-form expression by focusing on a specific scenario. Specifically, [14] provides the error rate analysis for typical SM-MIMO in different fading channels, and [15] provides the error rate analysis for the more general category of SM-based schemes. In contrast to them, our approximation is specifically proposed for Rayleigh fading channel and considers SM-based schemes without transmit diversity resulting in a more compact and simplified expression.

Notation: $\mathbf{x}^H$ and $\|\mathbf{x}\|$ represent the conjugate transpose, and l_2-norm of $\mathbf{x}$. We denote $\mathbf{I}_N$ as a $N \times N$ identity matrix.

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II. Models for Mode Selection

A. System and Signal Models

In this work, we consider the point-to-point MIMO system equipped with N_t transmit antennas, N_r receive antennas, and several RF chains capable of being switched on/off. We adopt SM-based MIMO to convey information bits, and consider the large-scale fading loss and channel spatial correlations perfectly known at the transmitter. Given a pre-defined transmission mode set $\mathbf{\Phi}$ with size M, our goal is to select the best mode from $\mathbf{\Phi}$ via using the large-scale fading loss and channel correlations. By the result of mode selection, the information bits are converted to the SM-based signal for transmission. The receiver employing the maximum likelihood (ML) detector [6] is then adopted for detection. The described system model is illustrated in Fig. 1.

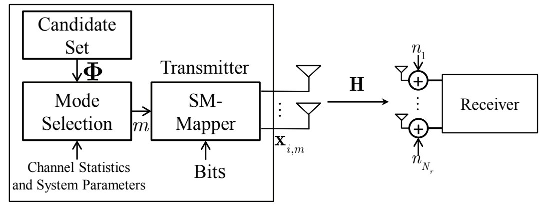

Fig. 1: System model for the SM-based MIMO with mode selection.

We consider Rayleigh fading channels and use the Kronecker model to describe effects of spatial correlations. Consider the selected mode m to activate $N_{a,m} \leq \min(N_t, N_r)$ antennas simultaneously at each time instant, where $\min(N_t, N_r)$ is the minimum of N_t and N_r. The flat-fading baseband MIMO signal model is given by

$$\mathbf{y} = \sqrt{\frac{G_a P_{tr,m}}{d_{loss}}}\mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2}\mathbf{x}_{i,m} + \mathbf{n}, \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is the received signal; $\mathbf{H}_w \in \mathbb{C}^{N_r \times N_t}$ is the uncorrelated Rayleigh fading channel matrix whose elements are independent and identically distributed (i.i.d.) complex white Gaussian random variables with zero mean and unit variance; $\mathbf{R}_t \in \mathbb{C}^{N_t \times N_t}$ and $\mathbf{R}_r \in \mathbb{C}^{N_r \times N_r}$ are the transmit correlation and receive correlation matrices, respectively, and both correlation matrices are hermitian and positive semi-definite; $P_{tr,m}$ is the average transmit power of mode m; G_a is the composite directive power gain of the transmit and receive antennas; d_{loss} is the large-scale fading loss; $\mathbf{x}_{i,m} \in \mathbb{C}^{N_t \times 1}$ is the ith complex transmitted SM-based signal of mode m; $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$ is the complex white Gaussian noise with zero mean and variance σ_n^2.

We consider the typical GSM model for the transmitted signal. Since only the activated antennas are embedded with APM symbols, the SM-based signal [3] is expressed as[1] $\mathbf{x}_{i,m} = \frac{1}{\sqrt{N_{a,m}}}(\sum_{k=1}^{N_{a,m}} \mathbf{e}_{(l_{i,m}^{(k)})} s_{k,i,m})$, where $s_{k,i,m}$ is the kth APM multiplexing stream whose signal constellation has size N_m and $E\{|s_{k,i,m}|^2\} = 1$; $\mathbf{e}_i$ is the ith standard unit vector; and $l_{i,m}^{(k)}$ is the indicating index of the kth used antenna of $\mathbf{x}_{i,m}$. The size of the active spatial constellation of mode m is $N_{l,m} = 2^{\lfloor \log_2 \binom{N_t}{N_{a,m}} \rfloor}$. The total number of constellation points is $N_{c,m} = (N_m)^{N_{a,m}} N_{l,m}$, and the transmission rate is $b_m = \log_2(N_{l,m}) + N_{a,m}\log_2(N_m)$. By considering all activated antennas to use identical APM symbol, i.e., $s_{k,i,m} = s_{l,i,m}, \forall k \neq l$, GSM-MIMO can be used without multiplexing (MUX) [2]. The transmission rate then reduces to $b_m = \log_2(N_{l,m}) + \log_2(N_m)$.

[1]We consider the typical SM-based signal and transmitted symbols in different activated antennas to employ the identical APM constellation for simplicity. The framework can be flexibly used with arbitrary SM-based transmission without time/frequency dispersion and transmit diversity design. One example is the asymmetric signal constellation design in [7].

B. Power Consumption Model

The power consumption model at the transmitter with mode m includes both the transmit power consumption and the circuit power consumption, and is given by $P_{tot,m} = P_{cc,m} + \eta^{-1}\kappa_m P_{tr,m}$, where $P_{cc,m}$ is the overall circuit power consumption of mode m, η is the efficiency of the power amplifier, and κ_m is the peak-to-average power ratio (PAPR) of the adopted APM of mode m. By inspecting the power model and including the effect of the number of active RF chains, the total power consumption [16], [17] of the mode m can be expressed as

$$\begin{aligned} P_{tot,m} =& R_{c,m}P_c + N_{a,m}BP_b + P_f \\ &+ N_{a,m}P_{c1} + N_{a,m}BP_{c2} + N_{a,m}\eta^{-1}\kappa_m P_{T,m}, \end{aligned} \tag{2}$$

where $R_{c,m} = Bb_m$ is the transmission rate of mode m; $P_{T,m} = \frac{P_{tr,m}}{N_{a,m}}$ is the average transmit power per antenna; B is the bandwidth; P_c is the power consumption related to channel coding; P_b is the power consumption factor related to the baseband processing; P_f is the fixed circuit power consumption; P_{c1} and P_{c2} are the circuit power consumption factors proportional to different system parameters. We note that only the transmitter power consumption is considered for simplicity, and the framework can be extended to involve arbitrary power model.

III. Proposed Transmission Mode Selections

We consider the system equipped with pre-defined modes in $\mathbf{\Phi}$. By the availability of system parameters, large-scale fading loss, and spatial correlation matrices, the system can be optimized for different transmission goals by selecting the most suitable mode. Here we first elaborate the SER/BER approximation for designing the mode selection approaches. Then mode selection approaches are proposed to maximize SE and EE, respectively.

A. SER/BER Approximation for SM-Based MIMO Systems

Here we provide the closed-form SER/BER approximation for SM-based MIMO systems in Rayleigh fading channels. Consider the ML detector and the average signal-to-noise power ratio (SNR) given as $\rho_m = \frac{G_a P_{tr,m}}{\sigma_n^2 d_{loss}}$. Conditioned on a given channel realization, the SER $p_{ser}^{(m)}$ BER $p_{ber}^{(m)}$ are upper bounded as [18] $p_{ser}^{(m)} \leq \sum_{i=1}^{N_{c,m}}\sum_{j=1,i\neq j}^{N_{c,m}} \frac{Q(\sqrt{D})}{N_{c,m}}$ and $p_{ber}^{(m)} \leq \sum_{i=1}^{N_{c,m}}\sum_{j=1,i\neq j}^{N_{c,m}} \frac{N(i,j)Q(\sqrt{D})}{N_{c,m}\log_2 N_{c,m}}$, respectively, where $D = \frac{\rho_m}{2}\|\mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2}(\mathbf{x}_{i,m} - \mathbf{x}_{j,m})\|^2$, $Q(.)$ is the Q-function, and $N(i,j)$ is the number of bits in error when

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TABLE I: Transmission Modes Used in Fig. 2

Mode 1	$N_{a,m}=1, b_m=4$	Mode 2	$N_{a,m}=1, b_m=5$
Mode 3	$N_{a,m}=1, b_m=7$	Mode 4	$N_{a,m}=1, b_m=9$
Mode 5	$N_{a,m}=2, b_m=6$	Mode 6	$N_{a,m}=2, b_m=8$

$\mathbf{x}_i$ is erroneously detected as $\mathbf{x}_j$. Define the pair-wise error probability as $P(\mathbf{x}_{i,m}\rightarrow\mathbf{x}_{j,m})=E\Big\{Q(\sqrt{D})\Big\}$. We have the following Approximation.

Approximation: Consider $\mathbf{R}_r = \mathbf{I}_{N_r}$ and $\mathbf{R}_r$ is with distinct non-zero eigenvalues, the pair-wise error probability $P(\mathbf{x}_{i,m}\rightarrow\mathbf{x}_{j,m})$ can be respectively approximated as

$$\frac{(2N_r-1)!}{N_r!(N_r-1)!}\Big(\frac{1}{\rho_m\psi_{ij,m}}\Big)^{N_r};\frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P}\xi_k}\Big(\frac{1}{\rho_m\psi_{ij,m}}\Big)^{P},\quad(3)$$

where $\psi_{ij,m}=(\mathbf{x}_{i,m}-\mathbf{x}_{j,m})^H\mathbf{R}_t(\mathbf{x}_{i,m}-\mathbf{x}_{j,m})$; ξ_1,...,ξ_P are the distinct non-zero eigenvalues of $\mathbf{R}_r$; and $P\leq N_r$ is the rank of $\mathbf{R}_r$. The proof is in Appendix A.

Subsequently, by the Approximation, the SER/BER of the system using mode m can be approximately bounded by

$$E\{p_{ser}^{(m)}\}\lessapprox\frac{\frac{(2P-1)!}{P!(P-1)!}}{N_{c,m}}\frac{\rho_m^{-P}\psi_{c,m}}{\prod_{k=1}^{P}\xi_k}\quad(4)$$

and

$$E\{p_{ber}^{(m)}\}\lessapprox\frac{\frac{(2P-1)!}{P!(P-1)!}}{N_{c,m}\log_2 N_{c,m}}\frac{\rho_m^{-P}\psi_{c,m}^{ber}}{\prod_{k=1}^{P}\xi_k},\quad(5)$$

respectively, where $\psi_{c,m}=\sum_{i=1}^{N_{c,m}}\sum_{j=1,i\neq j}^{N_{c,m}}(\psi_{ij,m})^{-P}$ and $\psi_{c,m}^{ber}=\sum_{i=1}^{N_{c,m}}\sum_{j=1,i\neq j}^{N_{c,m}}N(i,j)\cdot(\psi_{ij,m})^{-P}$.

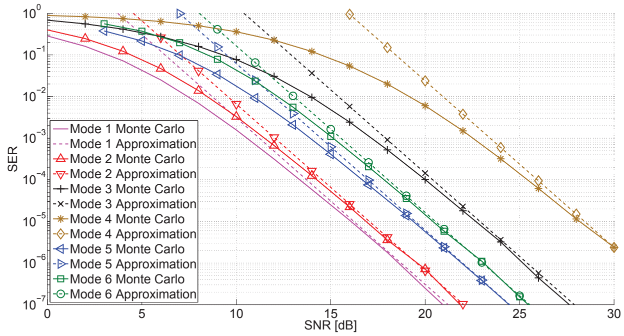
In Fig. 2, we evaluate the proposed SER approximation in SM-based MIMO systems with $N_t=8$, $N_r=4$, and different modes listed in Table I. In the figure, modes 1 to 4 adopt SM and modes 5 and 6 adopt GSM with MUX. Besides, the transmit and receive correlation matrices are generated by exponential correlation model [18] with real correlation factors, expressed as $(\mathbf{R}_t)_{kl}=\alpha_t^{|k-l|}$ and $(\mathbf{R}_r)_{kl}=\alpha_r^{|k-l|}$, respectively, where $(\mathbf{R})_{kl}$ indicates the entry in the kth row and lth column of $\mathbf{R}$; α_t and α_r are the correlation factors. From the figures, we can observe that the proposed approximation is close to monte carlo results as the SER is lower than 10^{-4}. Therefore, the proposed approximation is accurate in the typical operation regime where the SER is lower than 10^{-5}. Note that the BER approximation exhibits similar accuracy as in the SER approximation, albeit the results are omitted for simplicity. In the following, we propose mode selection approaches via using the approximation, and consider only the SER requirement for brevity. The extension to using the BER requirement can be straightforward.

B. Spectral Efficiency (SE) and Energy Efficiency (EE) Based Transmission Mode Selections

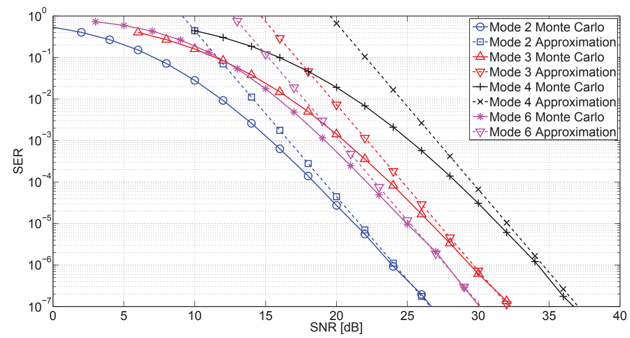
Consider to maximize SE with a given average transmit power P_{ave} via mode selection. The optimization problem is given as

$$\max_{m\in\mathbf{\Phi}}\ b_m\quad\text{s.t.}\quad P_{tr,m}=P_{ave},p_{e,m}\leq p_{req},\quad(6)$$

where $p_{e,m}$ is the SER of mode m and p_{req} is the SER/BER requirement. Since the provided approximation is tight at the region of typical error rate requirements, we consider to



(a) Uncorrelated channels with $\alpha_t=\alpha_r=0$.



(b) Correlated channels with $\alpha_t=\alpha_r=0.7$.

Fig. 2: SER approximation of SM-based MIMO systems with $N_t=8$, $N_r=4$ in Rayleigh fading channels.

approximate the SER in (6) by exploiting the proposed SER approximation in (4). Then, with $P_{tr,m}=P_{ave}$, we can derive a closed-form approximation for (6) as

$$\max_{m\in\mathbf{\Phi}}\ b_m\quad\text{s.t.}\quad\frac{\psi_{c,m}}{N_{c,m}}\frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P}\xi_k}\Big(\frac{G_aP_{ave}}{\sigma_n^2d_{loss}}\Big)^{-P}\leq p_{req}.\quad(7)$$

The merit of (7) is its simple closed-form expression of the constraint. Then, as the size of candidate set is usually moderate with a small number of $N_{a,m}$ (limited number of RF chains for SM-based MIMO), we can simply solve (7) by exhaustively searching over all candidate modes in $\mathbf{\Phi}$. Besides, since the large-scale fading loss and spatial statistics are expected to vary slowly, the selection complexity is considered practically feasible. Moreover, the complexity can be further reduced through replacing the computations of $\psi_{c,m}$ with table look-up operations. (Refer the discussion to Section III-C). We note that the extension to using BER requirement is straightforward via using the BER approximation.

Now we consider to maximize EE. The optimization problem is given as

$$\begin{aligned}\max_{m\in\mathbf{\Phi},P_{tr,m}}\quad&\mu_m=\frac{R_{c,m}}{P_{tot,m}}\\ \text{s.t.}\quad&b_m\geq b_{req},P_{tr,m}\leq P_{ave},p_{e,m}\leq p_{req},\end{aligned}\quad(8)$$

where b_{req} is the rate requirement. By using (4) and the power model in (2), (8) can be simplified as

$$\begin{aligned}\max_{m\in\mathbf{\Phi},P_{T,m}}\quad&\mu_m=\frac{1}{P_c+\frac{P_f}{Bb_m}+\frac{N_{a,m}}{b_m}(P_b+\frac{P_{c1}}{B}+P_{c2}+\frac{\eta^{-1}\kappa_mP_{T,m}}{B})}\\ \text{s.t.}\quad&b_m\geq b_{req},P_{T,m}N_{a,m}\leq P_{ave}\\ &\frac{\psi_{c,m}}{N_{c,m}}\frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P}\xi_k}\Big(\frac{G_aP_{T,m}N_{a,m}}{\sigma_n^2d_{loss}}\Big)^{-P}\leq p_{req}.\end{aligned}\quad(9)$$

We consider the noise power given by $\sigma_n^2 = BN_0$, where N_0 is the noise power spectral density. With the intuition that the optimal EE must be achieved at the equality of the error rate constraint, (9) can be equivalently solved by using

$$\begin{aligned} \max_{m\in\mathbf{\Phi}} \quad & \mu_{m,e} \\ \text{s.t.} \quad & b_m \geq b_{req}, \ \frac{BN_0 d_{loss}}{G_a}\left[\frac{\psi_{c,m}}{N_{c,m}p_{req}} \frac{\frac{(2P-1)!}{P!(P-1)!}}{\prod_{k=1}^{P}\xi_k}\right]^{\frac{1}{P}} \leq P_{ave}, \end{aligned} \tag{10}$$

where

$$\begin{aligned} \frac{1}{\mu_{m,e}} &= P_c + \frac{P_f}{Bb_m} + \frac{N_{a,m}}{b_m}\left(P_b + \frac{P_{c1}}{B} + P_{c2}\right) \\ &+ d_{loss}\frac{N_0\eta^{-1}\kappa_m}{G_a b_m}\left(\frac{(2P-1)!}{P!(P-1)!}\frac{\psi_{c,m}}{p_{req}\cdot 2^{b_m}\cdot\prod_{k=1}^{P}\xi_k}\right)^{\frac{1}{P}}. \end{aligned} \tag{11}$$

Note that (10) is derived by first obtaining the $P_{T,m}$ at the equality of the error rate constraint, and then substituting the $P_{T,m}$ into the objective and constraint functions. With the objective and constraint functions being closed-form expressions, the EE of a certain mode satisfying the SER and power requirements can be easily computed. Then the mode providing the best EE can be found via using (10) and exhaustive search. Similar to the SE case, the selection can be extension to considering BER requirement and the complexity can be reduced by the look-up table.

C. Selection Complexity Reduction via Use of Look-Up Table

By previous derivations, we observe that, $\psi_{c,m}$ is invariant if the transmit correlation matrix is invariant. This unique feature can be exploited to reduce the complexity of the selection process, as we can replace the costly metric computations with the simple table look-ups. Specifically, since $\mathbf{\Phi}$ is predetermined, all $\psi_{c,m}$ can be pre-computed and stored in a look-up table. Then whenever $\psi_{c,m}$ is required, $\psi_{c,m}$ is attainable by looking up the pre-computed table. This avoids the need to real-time compute $\psi_{c,m}$ repeatedly, which significantly reduces the complexity. Interestingly, this complexity reduction approach can indeed be extended to situations with variant transmit correlation matrices. The extension can be performed by first quantizing the domain of the transmit correlation matrices, and then preparing look-up tables as in the invariant case for every quantized transmit correlation matrix, i.e., we prepare multiple look-up tables for conducting selection according to the correlation matrices possibly encountered. Subsequently, when implementing the selection process, we choose the most suitable look-up table for the selection while encountering different correlation matrices. We note that the specific quantization approach could be case-dependent and requires specific designs.

IV. Numerical Results of SE/EE Mode Selections

Here we evaluate the proposed SE and EE based selection approaches. The system and environment parameters used in the simulations are generally given as follows [16], [17]: $p_{req} = 10^{-6}$, $N_0 = -174$ (dBm/Hz), $B = 1$ (MHz), $G_a = 1$, $\eta = 0.35$, $P_c = 10^{-8}$, $P_b = 4.09 \times 10^{-9}$, $P_f = 0.1$, $P_{c1} = 0.04$, $P_{c2} = 1.3 \times 10^{-8}$. For the generation of the candidate set $\mathbf{\Phi}$, we consider the exhaustive inclusion of all

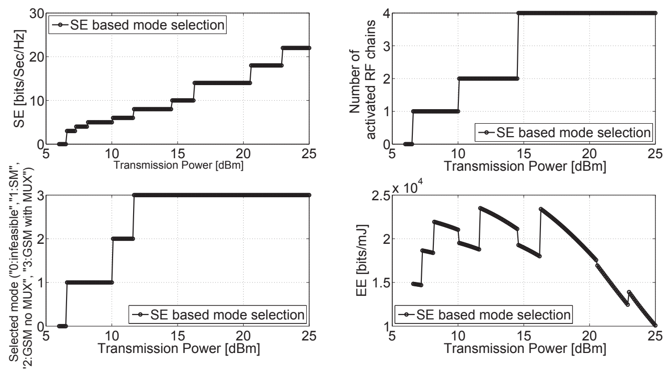


Fig. 3: SE based selection for MIMO system with $N_t = 8$, $N_r = 4$, and large-scale fading loss being $d_{loss} = 102$ dB in uncorrelated Rayleigh fading channels.

the feasible[2] transmission modes for every given transmission rate. Besides, all transmission modes satisfy $N_{a,m} \leq N_r$ and $3 \leq b_m \leq 22$ bits/sec/Hz.

In Fig. 3, we demonstrate the efficacy of the SE-based mode selection by changing P_{ave}. In the figure, the MIMO system with $N_t = 8$, $N_r = 4$, and $d_{loss} = 102$ dB is adopted in uncorrelated Rayleigh fading channels. From the figure, we can observe that the proposed approach can adapt the SE. Besides, as P_{ave} increases, the selection tends to activate more RF chains to provide larger SE and better utilization of spatial degrees of freedom (DoFs). Moreover, as the SE of the selected transmission mode increases to a very high value, we can observe the trend of the EE deterioration. This is because we inevitably require larger transmit power and more activated RF chains for higher SE. However, as can be observed in the right-bottom sub-figure, there are points where the increase of transmit power can benefit both the SE and EE. Hence, for the best operation strategy, the system needs to be operated around the beneficial points.

In Fig. 4, we demonstrate the efficacy and behavior of the EE based selection approach in the MIMO system with $N_t = 8$, $N_r = 4$ in uncorrelated Rayleigh fading channels. In Fig. 4a, we compare the proposed selection with ordinary modes without selection. In the figure, we observe that the proposed selection approach can outperform modes without selection, which shows the efficacy of the proposed selection approach. The behavior of proposed EE selection is shown in Fig. 4b. From the figure, we can observe the alteration of the number of active RF chains being: 2-4-2-1. The reasons are as follows. When the loss is small, the circuit power consumption dominates EE. Hence the number of active RF chains increases only when the increase introduces large benefit. Then as the fading loss increases, the transmit power consumption starts to dominate. Therefore, the selection process strives to maintain the power consumption by activating more RF chains and providing better utilization of spatial DoFs. Finally, as the power consumption continues to grow, the selection approach begins to reduce SE to obtain better EE. Since activating more RF chains inevitably provides higher SE in the considered SM-based architecture, the number of activated RF chains reduces

[2]We use BPSK, QPSK, 8-QAM, 16-QAM, 32-QAM, 64-QAM, 128-QAM, and 256-QAM; all the S-QAM constellations are rectangular.

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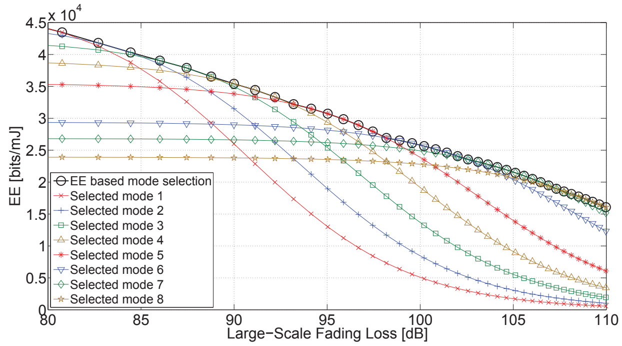
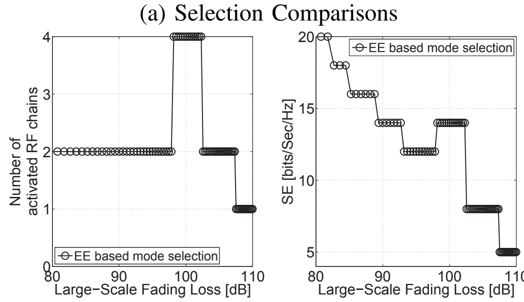


(a) Selection Comparisons



(b) Selection Behaviors

Fig. 4: EE based selection for MIMO systems with $N_t = 8$, $N_r = 4$ in uncorrelated Rayleigh fading channels.

till one. We note that only small number of modes in $\mathbf{\Phi}$ are presented in our figures where the system parameters, rate requirement, and spatial correlations are fixed for illustration convenience. While the environmental and system conditions could change for real systems, more modes would be selected and used for transmission.

V. Conclusions

In this work we propose a framework to select the mode with the best SE or EE while satisfying certain requirements from a pre-defined candidate set. The SER/BER approximation, which replaces the error rate constraint with elegant closed-form expression, is the key to the framework. It renders the selection problems easily solvable via exhaustive search. The framework can include all SM-based schemes without transmit diversity leading to significant improvements. Besides, it is practical with the low complexity and by using merely the slowly varying channel statistics.

An possible extension of the framework is to include SM-based schemes capable of providing transmit diversity by using the general SER/BER expression in [15]. However, there are still challenges for the extension, such as the simplification of the SER/BER expression and the unification of power model expressions. By resolving these challenges, the performance of the proposed framework can be improved.

Appendix A

We first consider $\mathbf{R}_r = \mathbf{I}_{N_r}$. Observing the result in (16) in [18], we have $P(\mathbf{x}_{i,m} \to \mathbf{x}_{j,m}) = \mu\left(\frac{\rho\psi_{ij,m}}{4}\right)^{N_r} \sum_{k=0}^{N_r-1} \binom{N_r-1+k}{k} \left[1 - \mu\left(\frac{\rho\psi_{ij,m}}{4}\right)\right]^k$, where $\psi_{ij,m} = (\mathbf{x}_{i,m} - \mathbf{x}_{j,m})^H \mathbf{R}_t (\mathbf{x}_{i,m} - \mathbf{x}_{j,m})$ and $\mu(x) = \frac{1}{2}\left(1 - \sqrt{\frac{1}{1+1/x}}\right)$. Then, assuming SNR is sufficiently large and exploiting the Taylor's expansion for ρ, the pair-wise error probability can be approximated as

$$P(\mathbf{x}_{i,m} \to \mathbf{x}_{j,m}) \approx \frac{(2N_r-1)!}{N_r!(N_r-1)!} \left(\frac{1}{\rho\psi_{ij,m}}\right)^{N_r} \qquad (12)$$

by keeping the first non-zero term of the expansion and discarding the others. Then, we consider $\mathbf{R}_r$ with ξ_1,...,ξ_P distinct non-zero eigenvalues and P is the rank of $\mathbf{R}_r$. According to the mathematical derivations in (4)-(14) in [18], we have $P(\mathbf{x}_{i,m} \to \mathbf{x}_{j,m}) = \sum_{k=1}^{P} \frac{\xi_k^{P-1}}{\prod_{l=1,k\neq l}^{P}(\xi_k - \xi_l)} \mu\left(\frac{\rho\psi_{ij,m}\xi_k}{4}\right)$. Again by using the Taylor's expansion, the pair-wise error probability can be approximated as

$$P(\mathbf{x}_{i,m} \to \mathbf{x}_{j,m}) \approx \frac{(2P-1)!}{P!(P-1)!} \frac{1}{\prod_{k=1}^{P}\xi_k} \left(\frac{1}{\rho\psi_{ij,m}}\right)^P. \quad (13)$$

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