Coded Modulation With Mismatched CSIT Over MIMO Block-Fading Channels

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***Abstract*—Reliable communication over delay-constrained multiple-input multiple-output (MIMO) block-fading channels with discrete inputs and mismatched (imperfect) channel state information at the transmitter (CSIT) is studied. The CSIT mismatch is modeled as Gaussian random variables, whose variances decay as a power of the signal-to-noise ratio (SNR). A special focus is placed on the large-SNR decay of the error and outage probabilities when power control with long-term power constraints is used. Without explicitly characterizing the corresponding power allocation algorithms, we derive the outage exponent as a function of the system parameters, including the CSIT noise variance exponent and the exponent of the peak power constraint. It is shown that CSIT, even if noisy, is always beneficial and leads to important gains in terms of exponents.**

***Index Terms*—Coded modulation, discrete input, diversity methods, large-deviation analysis, MIMO systems, singleton bound.**

I. Introduction

TEMPORAL power control across fading states can lead to dramatic improvement in the outage performance of block-fading channels [1], [2]. The intuition behind this phenomenon is that power saved in particularly bad channel conditions can be used in better channel realizations. Power control over block-fading channels was originally studied under the idealistic assumptions of perfect channel state information (CSI) at the transmitter (CSIT) and Gaussian signal constellations [1], [2]. Acquiring perfect CSIT is, however, a challenging task due to the temporal variation of wireless media, as well as due to the processing and transmission delay. This motivates a large body of works studying fading channels under less optimistic assumptions about the CSIT; see for example [3], [4] and references therein.

This work considers a multiple-input multiple-output (MIMO) block-fading channel with *discrete input*, where the transmitter has access to a noisy version of the CSI. Similarly to [5], we model the CSIT noise as Gaussian random variables whose variances decay as a negative power of the signal-to-noise ratio (SNR). Focusing on the high-SNR regime, we establish the diversity gain of MIMO block-fading channels under the noisy CSIT model of interest. The diversity–multiplexing tradeoff (DMT) [6] achieved by mismatched temporal power control over such a channel model has been considered in [5], [7], [8]. However, unlike in the DMT analysis where the code rate grows with the SNR, in the current work we keep the constellation size to be 2^M at all values of the SNR and we do not let the code rate scale with the SNR.

Such a noise-corrupted CSIT model is well motivated and studied in the literature; see for example [9]–[11]. The rate of decaying of the CSIT noise can also be related to practical parameters in wireless systems [7]. Unlike the constant-power variable-rate scenarios, studied e.g., in [5] and [12], we consider a power-controlled constant-rate system. In sharp contrast to the assumption of using Gaussian codebooks [5], [7], [8], [13]–[15], the current work assumes that the input symbols are taken from a general *discrete* distribution such as QAM or PSK. Spatial and temporal power control policies under the imperfect CSIT and BPSK signalling assumptions have also been considered in [16].

In this paper, we address the problem of analytically quantifying the diversity gain achieved by discrete input and imperfect CSIT. A key technical novelty in the analysis is that we *directly* relate the asymptotic power control rule to the elements of the noise-corrupted channel matrix, and not to its eigenvalues as in [7]. We show that the diversity gain of coded-modulation systems can only match that provided by the ideal Gaussian codebooks when the ratio between the code rate and the constellation size is sufficiently small. The results shed some light into the interplay in the high-SNR regime between the number of transmit and receive antennas, the number of fading blocks, the constellation size, the code rate, as well as the SNR exponent of the CSIT noise variance and the peak exponent constraint.

This paper is organized as follows. The system model is given in Section II. Section III introduces the fundamental concepts underlying our analysis. Section IV presents our main results for the outage exponent with imperfect CSIT. Section V draws our final considerations. The proofs of our results can be found in the Appendices.

II. System Model

Consider transmission over a block-fading channel with B subchannels, where each subchannel has $N_{\rm t}$ transmit and $N_{\rm r}$ receive antennas. The mutually independent channel matrices $\boldsymbol{H}_1, \ldots, \boldsymbol{H}_B \in \mathbb{C}^{N_{\rm r}\times N_{\rm t}}$ have independent and identically distributed (i.i.d.) complex Gaussian components with zero mean and unit variance. The channel matrices are constant during one fading block but change from one block to the other according

Manuscript received January 01, 2009; revised December 16, 2009. Date of current version October 20, 2010. The material in this paper was presented (in part) at the IEEE International Symposium on Information Theory, Seoul, Korea, June-July 2009.

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Communicated by G. Taricco, Associate Editor for Communications.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIT.2010.2070250

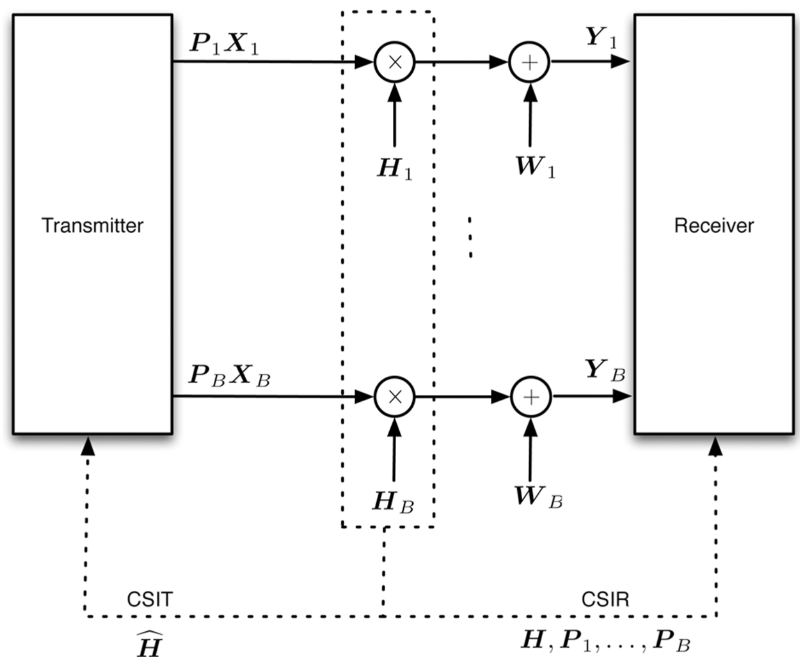


Fig. 1. System model and CSI assumptions.

to some ergodic and stationary Gaussian process. This models a typical delay-limited scenario in wireless communications, where the delay constraint dictated by higher-layer applications prevents the system from fully exploiting time diversity [1].

The corresponding discrete-time complex baseband input-output relation for the bth subchannel can be written as

$$\boldsymbol{Y}_b = \boldsymbol{H}_b\boldsymbol{P}_b\boldsymbol{X}_b + \boldsymbol{W}_b \tag{1}$$

where $\boldsymbol{Y}_b \in \mathbb{C}^{N_\mathrm{r}\times L}$ is the received signal matrix corresponding to block b, $\boldsymbol{X}_b \in \mathbb{C}^{N_\mathrm{t}\times L}$ is the transmitted signal matrix in block b, $\boldsymbol{P}_b \in \mathbb{C}^{N_\mathrm{t}\times N_\mathrm{t}}$ is the diagonal square-root power allocation matrix, and $\boldsymbol{W}_i \in \mathbb{C}^{N_\mathrm{r}\times L}$ denotes the complex additive white Gaussian noise matrix whose entries are i.i.d. with zero mean and unit variance. We denote the block length by L. Hence, a codeword corresponds to BL channel uses. We further define $\boldsymbol{H} \triangleq \mathrm{diag}(\boldsymbol{H}_1,\ldots,\boldsymbol{H}_B) \in \mathbb{C}^{BN_\mathrm{r}\times BN_\mathrm{t}}$ and $\boldsymbol{P} = \mathrm{diag}(\boldsymbol{P}_1,\ldots,\boldsymbol{P}_B) \in \mathbb{C}^{BN_\mathrm{t}\times BN_\mathrm{t}}$. While in most of the paper we will focus on power allocation, i.e., $\boldsymbol{P}$ being diagonal, there is some gain to be achieved for more general precoding matrices $\boldsymbol{P}$, as it will be shown later.

We assume perfect CSI at the receiver (CSIR), i.e., the receiver has perfect knowledge about all the channel gains and the powers $\boldsymbol{P}_b$. Furthermore, we assume that the transmitter has access to a noisy version $\hat{\boldsymbol{H}}_b$ of the true channel realization $\boldsymbol{H}_b$, so that

$$\boldsymbol{H}_b = \hat{\boldsymbol{H}}_b + \boldsymbol{E}_b, \quad b = 1,\ldots,B \tag{2}$$

where $\boldsymbol{E}_b \in \mathbb{C}^{N_\mathrm{r}\times N_\mathrm{t}}$ is the CSIT noise matrix, independent of $\hat{\boldsymbol{H}}_b$, with i.i.d. Gaussian components with zero mean and variance σ_e^2. This model of the CSIT has been well motivated in many different contexts, such as in scenarios with delayed feedback, noisy feedback, or in systems exploiting channel reciprocity [9], [10]. We further assume, as in [5], that the CSIT noise variance decays as a power of the SNR

$$\sigma_\mathrm{e}^2 = \mathrm{SNR}^{-d_\mathrm{e}} \tag{3}$$

for some $d_\mathrm{e} > 0$. Thus, we consider a family of channels where the second-order statistic of the CSIT noise varies with SNR. If the CSIT for example is estimated from the reverse link due to reciprocity, its quality will depend on the SNR of reverse link and not the forward link. However, while the SNRs of the forward and reverse links are different, any constant difference will be fully captured by changing the values of d_e.

For convenience, we introduce the normalized channel gains

$$\bar{\boldsymbol{H}}_b = \frac{\sqrt{2}}{\sigma_\mathrm{e}}\boldsymbol{H}_b \tag{4}$$

and define $\bar{\boldsymbol{H}} \triangleq \mathrm{diag}(\bar{\boldsymbol{H}}_1,\ldots,\bar{\boldsymbol{H}}_B)$. Given $\hat{\boldsymbol{H}}_b$ then $\bar{\boldsymbol{H}}_b$ is a complex Gaussian matrix with mean $\frac{\sqrt{2}}{\sigma_\mathrm{e}}\hat{\boldsymbol{H}}_b$ and entries having a scaled unit variance. Let $\gamma_{b,t,r} \triangleq |h_{b,t,r}|^2$ and $\theta_{b,t,r}$, respectively, denote the fading power gain and phase corresponding to the link between transmit antenna t, receive antenna r at block b. Then define $\bar{h}_{b,t,r} \triangleq \frac{\sqrt{2}}{\sigma_\mathrm{e}}h_{b,t,r}$ and $\bar{\gamma}_{b,t,r} \triangleq |\bar{h}_{b,t,r}|^2$.

The system model and CSI assumptions are summarized in Fig. 1.

III. Preliminaries

We assume transmission at a fixed-rate R using a coded modulation scheme $\mathcal{M} \subset \mathbb{C}^{N_\mathrm{t}\times BL}$ of length BL constructed over a signal constellation $\mathcal{X} \subset \mathbb{C}$ of size 2^M such as 2^M-PSK or QAM. We denote the codewords of $\mathcal{M}$ by $\boldsymbol{X} = (\boldsymbol{X}_1,\ldots,\boldsymbol{X}_B) \in \mathbb{C}^{N_\mathrm{t}\times BL}$. We assume that the signal constellation $\mathcal{X}$ has zero mean and is normalized in energy, i.e., $\mathbb{E}[X] = 0$ and $\mathbb{E}[|X|^2] = 1$, where X denotes the corresponding random variable. We denote the vector input distribution as

$Q(\boldsymbol{x})$ with $\boldsymbol{x} \in \mathcal{X}^{N_\mathrm{t}}$. With these assumptions, the instantaneous input-output mutual information of the channel is given by

$$I(\boldsymbol{H}) = \frac{1}{B}\sum_{b=1}^{B} I_{\mathcal{X}}(\boldsymbol{P}_b \boldsymbol{H}_b) \tag{5}$$

where

$$I_{\mathcal{X}}(\boldsymbol{S}) = \mathbb{E}\left[\log_2 \frac{e^{-\|\boldsymbol{y}-\boldsymbol{S}\boldsymbol{x}\|^2}}{\sum_{\boldsymbol{x}'\in\mathcal{X}^{N_\mathrm{t}}} Q(\boldsymbol{x}')e^{-\|\boldsymbol{y}-\boldsymbol{S}\boldsymbol{x}'\|^2}}\right] \tag{6}$$

is the input-output mutual information of an additive white Gaussian noise (AWGN) MIMO channel with channel matrix $\boldsymbol{S}$ using the signal constellation $\mathcal{X}^{N_\mathrm{t}}$ with probabilities $Q(\boldsymbol{x})$, $\boldsymbol{x} \in \mathcal{X}^{N_\mathrm{t}}$. The outage probability is commonly defined as in [17] and [18]

$$P_{\mathrm{out}}(R) \triangleq \Pr\{I(\boldsymbol{H}) < R\}. \tag{7}$$

In this work, we are interested in the SNR exponents [6], [19], i.e.,

$$d^\star \triangleq \sup_{\mathcal{M}\in\mathcal{F}} \lim_{\mathrm{SNR}\to\infty} -\frac{\log P_e(\mathrm{SNR},\mathcal{M})}{\log \mathrm{SNR}} \tag{8}$$

where the supremum is taken over all coded modulation schemes $\mathcal{M}$ in the family $\mathcal{F}$. We adopt the notation $g(\mathrm{SNR}) \doteq \mathrm{SNR}^a \Leftrightarrow \lim_{\mathrm{SNR}\to\infty} \frac{\log g(\mathrm{SNR})}{\log \mathrm{SNR}} = a$.

In the case of no CSIT, it has been shown in [20]–[22] that the pairwise error probability (PEP) decays with SNR exponent $d_{\mathrm{sb}}(R)$ given by the Singleton bound on the block-diversity of the coded modulation scheme $\mathcal{M}$

$$d_{\mathrm{sb}}(R) \triangleq N_\mathrm{r}\left(1 + \left\lfloor B\left(N_\mathrm{t} - \frac{R}{M}\right)\right\rfloor\right) \tag{9}$$

with $\lfloor x \rfloor$ being the largest integer that is not larger than x and $\lceil x \rceil$ being the smallest integer that is not smaller than x.

Due to the availability of a noisy version of the channel $\hat{\boldsymbol{\gamma}}$, the transmitter can adapt the transmitted powers $\boldsymbol{P}_b$ to the channel conditions. In this work, we consider an average power constraint, such that

$$\mathbb{E}\left[\frac{1}{B}\sum_{b=1}^{B} \mathrm{tr}\left(\boldsymbol{P}_b^2(\hat{\boldsymbol{H}})\right)\right] \le \mathrm{SNR}. \tag{10}$$

The SNR herein has the meaning of the average transmit power over infinitely many fading blocks. It is well known that power allocation with average power constraints yields significant gains with respect to power allocation with peak power constraints both in terms of exponents and absolute outage probability [1]. In order to give a more accurate characterization of the system behavior under practical peak-to-average power limitations, we also introduce a peak-to-average power constraint of the form

$$\frac{1}{B}\sum_{b=1}^{B} \mathrm{tr}\left(\boldsymbol{P}_b^2(\hat{\boldsymbol{H}})\right) \le \mathrm{SNR}^{d_{\mathrm{peak}}} \tag{11}$$

where d_{peak} is interpreted as the peak-to-average power SNR exponent. The case $d_{\mathrm{peak}} = 1$ represents a system whose allocated power is dominated by the peak-power constraint. Asymptotically, this yields the same exponent as that of a system with no power control. By allowing d_{peak} to take an arbitrary value, we can model a family of systems with different behavior in the peak power constraint. Note that in the high-SNR regime of interest, we can for example scale the right hand side of (11) by a constant without changing any conclusion. That is, any constant, finite ratios between the peak and the average power provide the same asymptotic behavior as $d_{\mathrm{peak}} = 1$.

The corresponding minimum-outage power allocation rule is the solution to the following problem:

$$\begin{cases} \text{Minimize} & P_{\mathrm{out}}(R) \\ \text{subject to,} & \mathbb{E}\left[\frac{1}{B}\sum_{b=1}^{B}\mathrm{tr}\left(\boldsymbol{P}_b^2(\hat{\boldsymbol{H}})\right)\right] \le \mathrm{SNR} \\ & \frac{1}{B}\sum_{b=1}^{B}\mathrm{tr}\left(\boldsymbol{P}_b^2(\hat{\boldsymbol{H}})\right) \le \mathrm{SNR}^{d_{\mathrm{peak}}} \end{cases}. \tag{12}$$

Recall that we constrain $\boldsymbol{P}_b(\hat{\boldsymbol{H}})$ to be diagonal with nonnegative elements. Solving this problem even numerically is difficult in general, given our noisy CSIT model and the discreteness of $\mathcal{X}$.

IV. Asymptotic Behavior of the Outage Probability

A. Main Results

In this section, we study the asymptotic behavior of the error probability. In particular, our main results in terms of SNR exponents are divided into achievability and converse, and are stated as follows.

Proposition 1 (Achievability): Consider transmission at rate R over a MIMO block-fading channel described by (1) with Rayleigh fading, mismatched CSIT modeled by (2) and inputs drawn from $\mathcal{X}$. The transmitter uses power control with an average power constraint (10) and a peak-to-average power constraint (11). Then, the following exponents are achieved by random coding:

$$d^{(\mathrm{r})}(R, d_\mathrm{e}, d_{\mathrm{peak}}) = \begin{cases} d^{(\mathrm{r})}(R)d_{\mathrm{peak}} & d_{\mathrm{peak}} \le 1 + d^{(\mathrm{r})}(R)d_\mathrm{e} \\ d^{(\mathrm{r})}(R)\left(1 + d^{(\mathrm{r})}(R)d_\mathrm{e}\right) & d_{\mathrm{peak}} > 1 + d^{(\mathrm{r})}(R)d_\mathrm{e} \end{cases} \tag{13}$$

where

$$d^{(\mathrm{r})}(R) \triangleq N_\mathrm{r}\left\lceil B\left(N_\mathrm{t} - \frac{R}{M}\right)\right\rceil. \tag{14}$$

Proof: See Appendix A. ■

Proposition 2 (Converse): Consider transmission at rate R over a MIMO block-fading channel described by (1) with Rayleigh fading, mismatched CSIT modeled by (2) and inputs drawn from $\mathcal{X}$. The transmitter uses power control with an average power constraint (10) and a peak-to-average power constraint (11). Then, the outage exponents are given by

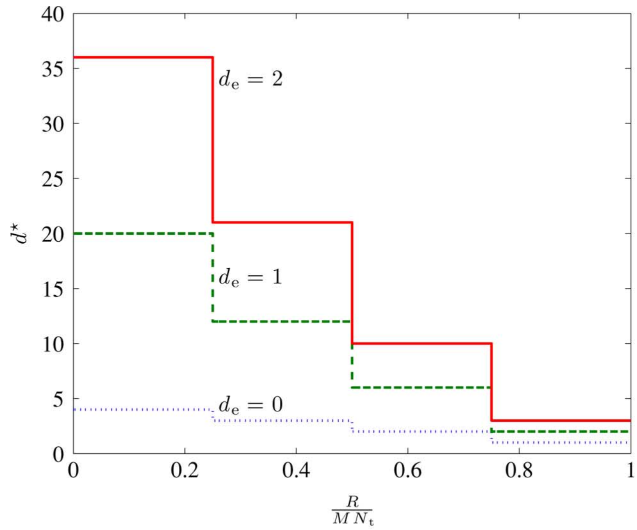
$$d_{\mathrm{out}}(R, d_\mathrm{e}, d_{\mathrm{peak}}) = \begin{cases} d_{\mathrm{sb}}(R)d_{\mathrm{peak}} & d_{\mathrm{peak}} \le 1 + d_{\mathrm{sb}}(R)d_\mathrm{e}, \\ d_{\mathrm{sb}}(R)\left(1 + d_{\mathrm{sb}}(R)d_\mathrm{e}\right) & d_{\mathrm{peak}} > 1 + d_{\mathrm{sb}}(R)d_\mathrm{e} \end{cases} \tag{15}$$

where $d_{\mathrm{sb}}(R)$ is given by (9).

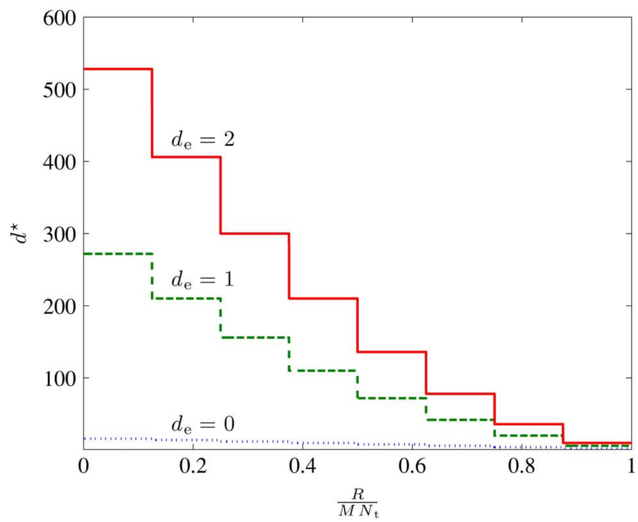
Proof: See Appendix C. ■

The above results yield the following theorem.

Theorem 1: Consider transmission at rate R over a MIMO block-fading channel described by (1) with Rayleigh fading, mismatched CSIT modeled by (2) and inputs drawn from $\mathcal{X}$.



(a)



(b)

Fig. 2. Outage exponents for $B = 4$ and $d_{\text{peak}} > 1 + md_e d_{\text{sb}}(R)$. (a) $N_t = N_r = 1$. (b) $N_t = N_r = 2$.

The transmitter uses power control with an average power constraint (10) and a peak-to-average power constraint (11). Then, the optimal SNR exponent is given by

$$d_{\text{out}}(R, d_e, d_{\text{peak}}) = \begin{cases} d_{\text{sb}}(R)d_{\text{peak}} & d_{\text{peak}} \leq 1 + d_{\text{sb}}(R)d_e \\ d_{\text{sb}}(R)\left(1 + d_{\text{sb}}(R)d_e\right) & d_{\text{peak}} > 1 + d_{\text{sb}}(R)d_e \end{cases} \tag{16}$$

whenever $d_{\text{sb}}(R)$ is continuous.

Remark that the random coding exponent $d^{(r)}(R, d_e, d_{\text{peak}})$ equals $d_{\text{out}}(R, d_e, d_{\text{peak}})$ only when $d^{(r)}(R) = d_{\text{sb}}(R)$, i.e., when $d_{\text{sb}}(R)$ is continuous. This is due to a technical detail in the proof, as a result of which random codes cannot achieve the discontinuity points in $d_{\text{sb}}(R)$. Note, however, that there exist explicit coding schemes that can achieve them [22].

In order to illustrate the operational significance of the above results, in Fig. 2 we plot the outage exponents for $B = 4$ with no CSIT (or $d_e = 0$) and with noisy CSIT with $d_e = 1, 2$ when $d_{\text{peak}} > 1 + d_e d_{\text{sb}}(R)$. We consider two cases: the single-input single-output case, shown in Fig. 2(a) and the MIMO case with $N_t = N_r = 2$, shown in Fig. 2(b). As we observe from the figure, increasing d_e yields a better exponent. We can further observe the large improvement due to MIMO. Note that when the CSIT is perfect the exponent is infinitely large [23]. Observe, however, that even in the presence of imperfect CSIT, large gains are possible by using power control, with respect to the uniform power allocation case. In many practical systems we typically have $d_e < 1$ and that in such scenarios d_e can be related to the Doppler shift [7]. In principle, achieving $d_e > 1$ may also be possible by means of power control in the feedback link, provided that the CSIR of the forward link is *perfect* [13]. Note that our main result in Theorem 1 (and Theorem 2) also holds for nonzero-mean $\boldsymbol{H}_b$'s (Rician fading), because the asymptotic diversity gain only captures the slope of the outage probability, which is the same for zero and nonzero-mean $\boldsymbol{H}_b$'s.

To get some insight into the problem, let us take a closer look at the results of Theorem 1 in some special cases. In the extreme case $d_{\text{peak}} = 1$, which implies that the average and peak power have the same exponent, we obtain $d(R, d_e, 1) = d_{\text{sb}}(R)$, which is the outage exponent for a system with short-term power control, or no power control [20], [22]. Since a system with short-term power constraints cannot allocate power across multiple codewords, it is logical that the resulting outage exponent is independent of the quality of CSIT. Increasing d_{peak} subsequently leads to an improvement in the outage performance. However, when d_{peak} exceeds a certain threshold, there is no extra diversity gain by further increasing d_{peak} (the diversity gain is "saturated" due to the limitation on the accuracy of the CSIT). In other words, a stringent constraint on the peak power exponent leads to a lot more pronounced detrimental effect in the case of accurate CSIT (large d_e) than in the case of very noisy CSIT (small d_e).

In the limiting case $d_e \downarrow 0$, i.e., very noisy CSIT, we have $d(R, d_e, d_{\text{peak}}) \to d_{\text{sb}}(R)$, which is again exactly the outage exponent when there is no CSIT [20], [22]. In this case the outage exponent is also independent of d_{peak}, because the transmitter always uses a constant power of order SNR^1. The case $d_e \downarrow 0$ also represents the scenarios in some practical systems in which the CSIT noise variance does not decay with the SNR. If the CSIT noise variance has such an "error floor" in the high-SNR regime, then no extra diversity gain can be obtained from power control.

On the other hand, in case $d_e \to \infty$, i.e., when the CSIT noise variance decays exponentially or faster with the SNR, then $d(R, d_e) \to \infty$ for all $R < MN_t$, as long as the peak exponent constraint is also relaxed to satisfy $d_{\text{peak}} > 1 + d_{\text{sb}}(R)d_e$. For strictly positive and finite d_e, using power control, even with noisy CSIT, provides an extra diversity gain of $d_{\text{sb}}^2(R)d_e$ compared to the no-CSIT case, as long as the peak power constraint is sufficiently relaxed. The presence of the factor squared power also parallels with the diversity–multiplexing tradeoff result obtained in [7] for MIMO channels with Gaussian inputs.

B. Improving the Outage Exponent With Rotations

As noticed in a number of [24]–[27], employing a general precoding matrix that is not diagonal can results in gains in terms of mutual information and diversity exponent. In particular, we assume a block-diagonal precoding matrix

$$\boldsymbol{P} = \begin{pmatrix} \boldsymbol{P}_1 & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \ddots & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{P}_K \end{pmatrix} \in \mathbb{C}^{BN_t \times BN_t} \tag{17}$$

where the matrices $\boldsymbol{P}_1, \ldots, \boldsymbol{P}_K \in \mathbb{C}^{N \times N}$ are the K unitary rotation matrices of dimension $N \geq N_{\mathrm{t}}$ each, such that $NK = BN_{\mathrm{t}}$. It was shown in [26] that with no CSIT optimal exponent is given by

$$d_{\mathrm{out}} = d_{\mathrm{sb}}^{\mathrm{rot}}(R) \tag{18}$$

where

$$d_{\mathrm{sb}}^{\mathrm{rot}}(R) \triangleq NN_{\mathrm{t}}N_{\mathrm{r}}\left(1 + \left\lfloor \frac{B}{N}\left(1 - \frac{R}{MN_{\mathrm{t}}}\right)\right\rfloor\right). \tag{19}$$

With noisy CSIT, we have the following result, whose proof is completely analogous to that of the previous section combined with that of [26, Theorem 2].

Theorem 2: Consider transmission at rate R over a block-fading channel described by (1) with Rayleigh fading, mismatched CSIT modeled by (2) and the block-diagonal precoder described in (17) with an average power constraint (10). Then, the optimal SNR exponent is given by

$$\begin{aligned} &d_{\mathrm{out}}(R, d_{\mathrm{e}}, d_{\mathrm{peak}}) \\ &\quad = \begin{cases} d_{\mathrm{sb}}^{\mathrm{rot}}(R)d_{\mathrm{peak}} & d_{\mathrm{peak}} \leq 1 + d_{\mathrm{sb}}^{\mathrm{rot}}(R)d_{\mathrm{e}} \\ d_{\mathrm{sb}}^{\mathrm{rot}}(R)\left(1 + d_{\mathrm{sb}}^{\mathrm{rot}}(R)d_{\mathrm{e}}\right) & d_{\mathrm{peak}} > 1 + d_{\mathrm{sb}}^{\mathrm{rot}}(R)d_{\mathrm{e}}. \end{cases} \end{aligned} \tag{20}$$

whenever $d_{\mathrm{sb}}^{\mathrm{rot}}(R)$ is continuous.

The above theorem highlights the role of the precoder dimension N. This parameter is related to the complexity of decoding, as rotations require joint decoding, taking the output of blocks of N MIMO subchannels into account. We also observe that through trading complexity by increasing N, we can achieve a larger exponent, eventually obtaining that of Gaussian inputs [7]. We illustrate in Fig. 3 the effect of full-diversity rotation matrices on the outage exponent of the coded modulation system with mismatched CSIT. This precoding method clearly leads to a higher diversity gain even at high code rates, at the expense of increasing receiver complexity.

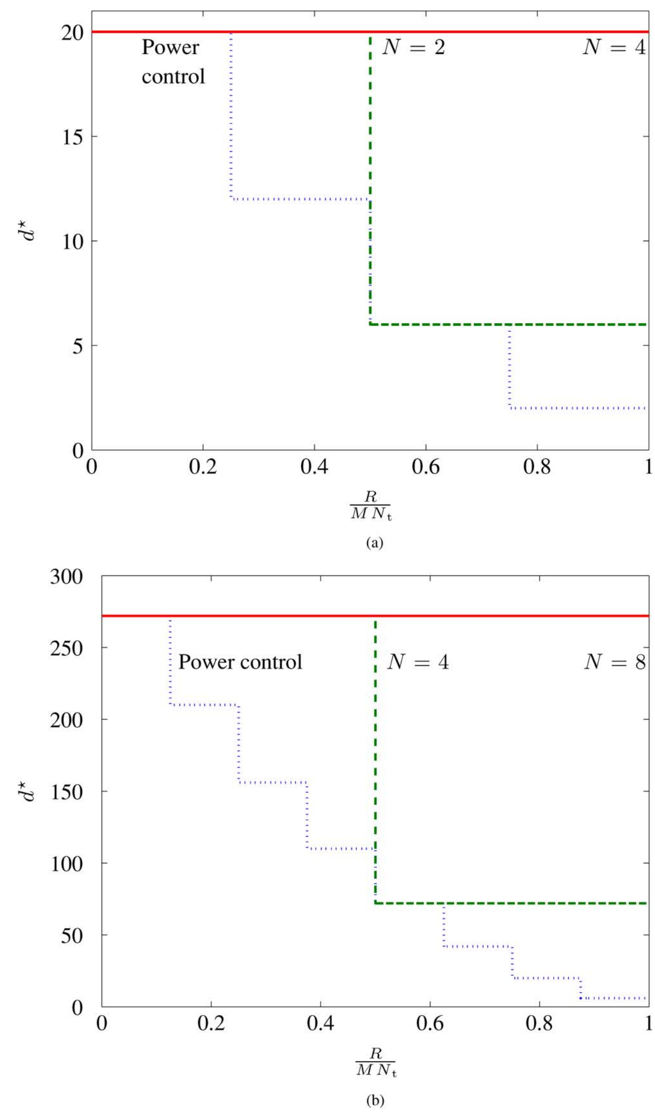


Fig. 3. Outage exponents with precoding for $B = 4$, $d_{\mathrm{e}} = 1$, $d_{\mathrm{peak}} > 1 + md_{\mathrm{e}}d_{\mathrm{sb}}(R)$. (a) $N_{\mathrm{t}} = N_{\mathrm{r}} = 1$, power control (dotted line), $N = 2$ (dashed line) and $N = 4$ (solid line). (b) $N_{\mathrm{t}} = N_{\mathrm{r}} = 2$, power control (dotted line), $N = 4$ (dashed line) and $N = 8$ (solid line).

V. Conclusion

We have studied the asymptotic behavior of the outage probability for coded modulation over MIMO block-fading channels under the assumption that the transmitter has access to a noisy version of the instantaneous channel gains. We showed that power control even with mismatched CSIT is still largely beneficial in improving the outage performance of the system. Our results shed some light into the interplay between different parameters in a coded modulation system, including the number of transmit and receive antennas, constellation size, the code rate, the quality of the CSIT, and the peak power requirement.

Appendix A
Proof of Proposition 1

In order to prove the achievability of the SNR-exponent in (13), we assume the following power allocation rule:

$$\boldsymbol{P}_b(\hat{\boldsymbol{H}}) = P(\hat{\boldsymbol{\Gamma}})\boldsymbol{I}_{N_{\mathrm{t}}}, \quad b = 1, \ldots, B \tag{21}$$

where $\hat{\boldsymbol{\Gamma}} \in \mathbb{R}^{B \times N_{\mathrm{t}} \times N_{\mathrm{r}}}$ is the matrix of power fading gains with entries $\hat{\gamma}_{b,t,r}$. Following the analysis in [6], define $\omega_{b,t,r} \triangleq \frac{-\log \gamma_{b,t,r}}{\log \mathrm{SNR}}$, $\hat{\omega}_{b,t,r} \triangleq \frac{-\log \hat{\gamma}_{b,t,r}}{\log \mathrm{SNR}}$ and $\bar{\omega}_{b,t,r} \triangleq \frac{-\log \bar{\gamma}_{b,t,r}}{\log \mathrm{SNR}}$; it then follows from (3) and (4) that $\bar{\omega}_{b,t,r} = \omega_{b,t,r} - d_{\mathrm{e}}$. Let $\boldsymbol{\Omega}, \hat{\boldsymbol{\Omega}}, \bar{\boldsymbol{\Omega}} \in \mathbb{R}^{B \times N_{\mathrm{t}} \times N_{\mathrm{r}}}$ be the matrices with entries $\omega_{b,t,r}, \hat{\omega}_{b,t,r}$ and $\bar{\omega}_{b,t,r}$ correspondingly. Further define $\pi(\hat{\boldsymbol{\Gamma}}) \equiv \pi(\hat{\boldsymbol{\Omega}}) \triangleq \frac{\log P(\hat{\boldsymbol{\Gamma}})}{\log \mathrm{SNR}} = \frac{\log P(\hat{\boldsymbol{\Omega}})}{\log \mathrm{SNR}}$. The power constraint (10) asymptotically becomes

$$\int \mathrm{SNR}^{2\pi(\hat{\boldsymbol{\Gamma}})} f(\hat{\boldsymbol{\Gamma}}) d\hat{\boldsymbol{\Gamma}} \dot{\leq} \mathrm{SNR}^1. \tag{22}$$

Notice that $\hat{\gamma}_{b,t,r}$ are mutually independent following the exponential distribution satisfying $\mathbb{E}[\hat{\gamma}_{b,t,r}] = \mathbb{E}[\|h_{b,t,r}\|^2] + \mathbb{E}[\|e_{b,t,r}\|^2] \doteq \mathrm{SNR}^0$. By changing the variable from $\hat{\boldsymbol{\Gamma}}$ to $\hat{\boldsymbol{\Omega}}$, we obtain

$$\int_{\hat{\boldsymbol{\Omega}} \in \mathbb{R}_+^{B \times N_{\mathrm{t}} \times N_{\mathrm{r}}}} \mathrm{SNR}^{2\pi(\hat{\boldsymbol{\Omega}})} \mathrm{SNR}^{-\sum_{b,t,r} \hat{\omega}_{b,t,r}} d\hat{\boldsymbol{\Omega}} \dot{\leq} \mathrm{SNR}^1. \tag{23}$$

Applying the Varadhan's integral lemma [28], it follows that[1]

$$\sup_{\hat{\boldsymbol{\Omega}}\in\mathbb{R}^{B\times N_{\rm t}\times N_{\rm r}}}\left\{2\pi(\hat{\boldsymbol{\Omega}})-\sum_{b,t,r}\hat{\omega}_{b,t,r}\right\}\leq 1. \tag{24}$$

Since outage probability is a nonincreasing function of transmit power, we conclude that with the optimal power allocation,

$$\pi(\hat{\boldsymbol{\Omega}})=\frac{1}{2}\min\left(d_{\rm peak},1+\sum_{b,t,r}\hat{\omega}_{b,t,r}\right) \tag{25}$$

where we need to introduce $d_{\rm peak}$ to take into account the peak constraint (11). It is worth pointing out that we herein directly relate the SNR exponent of the power level to the elements of the estimated channel matrix. This is in sharp contrast to the approach in [7], which relates the power control rule to the eigenvalues of the CSIT.

Consider transmission with rate R over the MIMO block-fading channel using random codes, where the symbols in $\boldsymbol{X}_b$ are i.i.d. uniformly drawn from the constellation $\mathcal{X}$. For a channel realization $\boldsymbol{\Omega}$ and CSIT $\hat{\boldsymbol{\Omega}}$, the pairwise error probability between $\boldsymbol{X}=(\boldsymbol{X}_1,\ldots,\boldsymbol{X}_B)$ and $\boldsymbol{X}'=(\boldsymbol{X}'_1,\ldots,\boldsymbol{X}'_B)$ is bounded by [29]

$$P_{\rm PEP}(\boldsymbol{X}\to\boldsymbol{X}'\,|\,\boldsymbol{\Omega},\hat{\boldsymbol{\Omega}})\dot{\leq}\exp\left(-\frac{1}{4}g^2(\boldsymbol{X},\boldsymbol{X}',\boldsymbol{\Omega},\hat{\boldsymbol{\Omega}})\right) \tag{26}$$

where

$$g^2(\boldsymbol{X},\boldsymbol{X}',\boldsymbol{\Omega},\hat{\boldsymbol{\Omega}})\triangleq\sum_{b}^{B}\sum_{\ell}^{L}\sum_{r}^{N_r}\left|\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})}\times{\rm SNR}^{-\frac{\omega_{b,t,r}}{2}}e^{i\theta_{b,t,r}}(x_{b,t,\ell}-x'_{b,t,\ell})\right|^2. \tag{27}$$

Here, $i=\sqrt{-1}$, and $x_{b,t,\ell}$ is the coded symbol transmitted by antenna t at time instant ℓ of block b.

By averaging over the random coding ensemble, the pairwise error probability is upper bounded by

$$\begin{aligned}P_{\rm PEP}^{(r)}(\boldsymbol{\Omega},\hat{\boldsymbol{\Omega}})&\dot{\leq}\prod_{b=1}^{B}\Bigg\{2^{-2MN_{\rm t}}\sum_{\boldsymbol{x},\boldsymbol{x}'\in\mathcal{X}^{N_{\rm t}}}\exp\Bigg(-\frac{1}{4}\\&\quad\times\sum_{r=1}^{N_{\rm r}}\left|\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\omega_{b,t,r}}{2}}e^{i\theta_{b,t,r}}(x_t-x'_t)\right|^2\Bigg)\Bigg\}^L\\&\doteq\exp\left(-BML\log(2)\left(2N_{\rm t}-\frac{1}{BM}T(\pi(\hat{\boldsymbol{\Omega}}),\boldsymbol{\Omega})\right)\right)\end{aligned} \tag{28}$$

where

$$\begin{aligned}T(\pi(\hat{\boldsymbol{\Omega}}),\boldsymbol{\Omega})&\triangleq\sum_{b=1}^{B}\log_2\Bigg(\sum_{\boldsymbol{x},\boldsymbol{x}'\in\mathcal{X}^{N_{\rm t}}}\exp\Bigg(-\frac{1}{4}\sum_{r=1}^{N_{\rm r}}\Bigg|\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\omega_{b,t,r}}{2}}\\&\qquad\times e^{i\theta_{b,t,r}}(x_t-x'_t)\Bigg|^2\Bigg)\Bigg).\end{aligned} \tag{29}$$

By summing over $2^{BRL}-1$ error events, the union bound on the word error probability, conditioned on channel realization $\boldsymbol{\Omega}$ and $\hat{\boldsymbol{\Omega}}$, is

$$\begin{aligned}&P_{\rm e}^{(r)}(\boldsymbol{\Omega},\hat{\boldsymbol{\Omega}})\\&\quad\dot{\leq}\min\Bigg\{1,\exp\Bigg(-BML\log(2)\\&\qquad\times\left(2N_{\rm t}-\frac{R}{M}-\frac{1}{BM}T(\pi(\hat{\boldsymbol{\Omega}}),\boldsymbol{\Omega})\right)\Bigg)\Bigg\}\\&\quad\doteq\min\Bigg\{1,\exp\Bigg(-BML\log(2)\\&\qquad\times\left(2N_{\rm t}-\frac{R}{M}-\frac{1}{BM}\hat{T}(\pi(\hat{\boldsymbol{\Omega}}),\bar{\boldsymbol{\Omega}})\right)\Bigg)\Bigg\}\end{aligned} \tag{30}$$

where

$$\begin{aligned}\hat{T}(\pi(\hat{\boldsymbol{\Omega}}),\bar{\boldsymbol{\Omega}})&\triangleq\sum_{b=1}^{B}\log_2\Bigg(\sum_{\boldsymbol{x},\boldsymbol{x}'\in\mathcal{X}^{N_{\rm t}}}\exp\Bigg(-\frac{1}{4}\\&\quad\times\sum_{r=1}^{N_{\rm r}}\left|\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\bar{\omega}_{b,t,r}+d_{\rm e}}{2}}e^{i\theta_{b,t,r}}(x_t-x'_t)\right|^2\Bigg)\Bigg).\end{aligned} \tag{31}$$

For any $\epsilon>0$, let $\mathcal{S}_b^{(\epsilon)}\triangleq\cup_{r=1}^{N_{\rm r}}\mathcal{S}_{b,r}^{(\epsilon)}$ and $\kappa_b\triangleq|\mathcal{S}_b^{(\epsilon)}|$, where

$$\mathcal{S}_{b,r}^{(\epsilon)}\triangleq\{t\in\{1,\ldots,N_{\rm t}\}:\bar{\omega}_{b,t,r}+d_{\rm e}<2\pi(\hat{\boldsymbol{\Omega}})-\epsilon\}. \tag{32}$$

For any $r\in\{1,\ldots,N_{\rm r}\}$, let $\bar{\omega}_{b,r}=\max_{t\in\mathcal{S}_{b,r}^{(\epsilon)}}\{\bar{\omega}_{b,t,r}\}$. If there exists $t\in\mathcal{S}_{b,r}^{(\epsilon)}$ such that $x_t\neq x'_t$, then

$$\lim_{{\rm SNR}\to\infty}\left|\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\bar{\omega}_{b,t,r}+d_{\rm e}}{2}}e^{i\theta_{b,t,r}}(x_t-x'_t)\right| \tag{33}$$

$$=\lim_{{\rm SNR}\to\infty}\left|{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\bar{\omega}_{b,r}+d_{\rm e}}{2}}\times\sum_{t=1}^{N_{\rm t}}{\rm SNR}^{\frac{\bar{\omega}_{b,r}-\bar{\omega}_{b,t,r}}{2}}e^{i\theta_{b,t,r}}(x_t-x'_t)\right| \tag{34}$$

$$\geq\lim_{{\rm SNR}\to\infty}\left|{\rm SNR}^{\pi(\hat{\boldsymbol{\Omega}})-\frac{\bar{\omega}_{b,r}+d_{\rm e}}{2}}\times\sum_{t\in\mathcal{S}_{b,r}^{(\epsilon)}}e^{i\theta_{b,t,r}}(x_t-x'_t)\right|=\infty \tag{35}$$

with probability 1 since $\theta_{b,t,r}$ are uniformly distributed in $[-\pi,\pi]$. Therefore

$$\hat{T}\left(\pi(\hat{\boldsymbol{\Omega}}),\bar{\boldsymbol{\Omega}}\right)\dot{\leq}\sum_{b=1}^{B}\log_2\left(\sum_{\boldsymbol{x},\boldsymbol{x}'\in\mathcal{X}^{N_{\rm t}}}\mathbb{1}\left\{x_t=x'_t,\forall t\in\mathcal{S}_b^{(\epsilon)}\right\}\right) \tag{36}$$

$$=\sum_{b=1}^{B}\log_2\left(\sum_{\boldsymbol{x}\in\mathcal{X}^{N_{\rm t}}}2^{M(N_{\rm t}-\kappa_b)}\right)=\sum_{b=1}^{B}M(2N_{\rm t}-\kappa_b). \tag{37}$$

[1]For notational convenience, $\sum_{b,t,r}$ is used to denote $\sum_{b=1}^{B}\sum_{t=1}^{N_{\rm t}}\sum_{r=1}^{N_{\rm r}}$; $\prod_{b,t,r}$ and $\bigcap_{b,t,r}$ are similarly defined.

Therefore, letting $L \to \infty$, it follows from (30) that

$$P_{\rm e}^{(r)}(\hat{\mathbf{\Omega}}, \bar{\mathbf{\Omega}}) \dot{\leq} \mathbb{1}\{(\hat{\mathbf{\Omega}}, \bar{\mathbf{\Omega}}) \in \mathcal{O}\} \tag{38}$$

where

$$\mathcal{O} \triangleq \left\{ \left(\hat{\mathbf{\Omega}}, \bar{\mathbf{\Omega}}\right) : \sum_{b=1}^{B} \kappa_b \leq \frac{BR}{M} \right\}. \tag{39}$$

Since $\hat{\omega}_{b,t,r}$'s are i.i.d., averaging over the fading statistic, the overall word error probability is asymptotically bounded by

$$P_{\rm e}^{(r)} \dot{\leq} \int_{\mathcal{O}} \prod_{b,t,r} f(\bar{\omega}_{b,t,r} \,|\, \hat{\omega}_{b,t,r}) f(\hat{\omega}_{b,t,r}) d\bar{\omega}_{b,t,r} \hat{\omega}_{b,t,r}. \tag{40}$$

Following the analysis in Appendix B, the SNR-exponent of random code achieves

$$\begin{aligned} d^{(r)}&(R, d_{\rm e}, d_{\rm peak}) \\ &= \inf_{\hat{\mathbf{\Omega}}, \bar{\mathbf{\Omega}} \in \bar{\mathcal{O}}} \left\{ \sum_{(b,t,r): -d_{\rm e} \leq \bar{\omega}_{b,t,r} = \hat{\omega}_{b,t,r} - d_{\rm e} < 0} \hat{\omega}_{b,t,r} \right. \\ &\quad \left. + \sum_{(b,t,r): \bar{\omega}_{b,t,r} \geq 0, \hat{\omega}_{b,t,r} \geq d_{\rm e}} \hat{\omega}_{b,t,r} + \bar{\omega}_{b,t,r} \right\} \end{aligned} \tag{41}$$

where

$$\begin{aligned} \bar{\mathcal{O}} \triangleq \mathcal{O} \cap &\left\{ \bigcap_{b,t,r} \{0 \leq \hat{\omega}_{b,t,r} < d_{\rm e}, \bar{\omega}_{b,t,r} = \hat{\omega}_{b,t,r} - d_{\rm e}\} \right. \\ &\left. \cup \{\hat{\omega}_{b,t,r} \geq d_{\rm e}, \bar{\omega}_{b,t,r} \geq 0\} \right\}. \end{aligned} \tag{42}$$

From (32) and (39), for all $\bar{\mathbf{\Omega}}, \hat{\mathbf{\Omega}} \in \mathcal{O}$, assume without loss of generality that for $r = 1, \ldots, N_{\rm r}$

$$\bar{\omega}_{b,t,r} \geq 2\pi(\hat{\mathbf{\Omega}}) - d_{\rm e} - \epsilon, \quad bB + t > \frac{BR}{M}. \tag{43}$$

Noting that for $\bar{\mathbf{\Omega}}, \hat{\mathbf{\Omega}} \in \bar{\mathcal{O}}$, the argument of the infimum in (41) is increasing with $\bar{\omega}_{b,t,r}$. It follows that the infimum in (41) is attained with

$$\bar{\omega}_{b,t,r} = 2\pi(\hat{\mathbf{\Omega}}) - d_{\rm e} - \epsilon, bB + t > \frac{BR}{M}. \tag{44}$$

Recalling from (25) that $2\pi(\hat{\mathbf{\Omega}}) = \min\{d_{\rm peak}, 1 + \sum_{b,t,r} \hat{\omega}_{b,t,r}\}$, we consider the following cases.

Case 1: $2\pi(\hat{\mathbf{\Omega}}) = d_{\rm peak} < d_{\rm e} + \epsilon$, it follows from (44) that $\bar{\omega}_{b,t,r} = d_{\rm peak} - d_{\rm e} - \epsilon < 0$, and thus $\hat{\omega}_{b,t,r} = \bar{\omega}_{b,t,r} + d_{\rm e}$ due to the set constraint $\bar{\mathcal{O}}$, when $bB + t > \frac{BR}{M}$. Therefore, the infimum in (41) is attained with

$$\bar{\omega}_{b,t,r} = \hat{\omega}_{b,t,r} - d_{\rm e} = \begin{cases} d_{\rm peak} - d_{\rm e} - \epsilon, & bB + t > \frac{BR}{M} \\ -d_{\rm e}, & \text{otherwise.} \end{cases} \tag{45}$$

The condition $\pi(\hat{\mathbf{\Omega}}) = d_{\rm peak}$ is satisfied since $\sum_{b,t,r} \hat{\omega}_{b,t,r} = d^{(r)}(R)(d_{\rm peak} - \epsilon) > d_{\rm peak}$ for sufficiently small ϵ. The SNR-exponent is then

$$d^{(r)}(R, d_{\rm e}, d_{\rm peak}) = \sum_{b,t,r} \hat{\omega}_{b,t,r} = d^{(\rm r)}(R)(d_{\rm peak} - \epsilon). \tag{46}$$

Case 2: $2\pi(\hat{\mathbf{\Omega}}) = d_{\rm peak} \geq d_{\rm e} + \epsilon$, it follows from (44) that $\bar{\omega}_{b,t,r} = \pi(\hat{\mathbf{\Omega}}) - d_{\rm e} - \epsilon \geq 0$, and thus $\hat{\omega}_{b,t,r} \geq d_{\rm e}$ due to the set constraint $\bar{\mathcal{O}}$, when $bB + t > \frac{BR}{M}$. The infimum in (41) is therefore attained with

$$\begin{cases} \bar{\omega}_{b,t,r} = d_{\rm peak} - d_{\rm e} - \epsilon \text{ and } \hat{\omega}_{b,t,r} = d_{\rm e}, & bB + t > \frac{BR}{M} \\ \bar{\omega}_{b,t,r} = -d_{\rm e} \text{ and } \hat{\omega}_{b,t,r} = 0, & \text{otherwise.} \end{cases} \tag{47}$$

The SNR-exponent is then

$$d^{(r)}(R, d_{\rm e}, d_{\rm peak}) = d^{(\rm r)}(R)(d_{\rm peak} - \epsilon). \tag{48}$$

The condition $\pi(\hat{\mathbf{\Omega}}) = d_{\rm peak} \geq d_{\rm e} + \epsilon$ is satisfies if $d_{\rm e} + \epsilon \leq d_{\rm peak} \leq 1 + d^{(\rm r)}(R)(d_{\rm peak} - \epsilon)$.

Case 3: If $\pi(\hat{\mathbf{\Omega}}) = 1 + \sum_{b,t,r} \hat{\omega}_{b,t,r}$, for (b', t') satisfying $b'B + t' > \frac{BR}{M}$,

$$\bar{\omega}_{b',t',r'} + d_{\rm e} = 1 + \sum_{b,t,r} \hat{\omega}_{b,t,r} - \epsilon > \hat{\omega}_{b',t',r'} \tag{49}$$

for $\epsilon < 1$. Therefore, noting the set constraint $\bar{\mathcal{O}}$, we have that $\hat{\omega}_{b,t,r} \geq d_{\rm e}$ and $\bar{\omega}_{b,t,r} \geq 0$ for $bB + t > \frac{BR}{M}$. The infimum is thus attained with

$$\hat{\omega}_{b,t,r} = \begin{cases} d_{\rm e}, & bB + t > \frac{BR}{M} \\ 0, & \text{otherwise} \end{cases} \tag{50}$$

and

$$\bar{\omega}_{b,t,r} = \begin{cases} 1 + d^{(\rm r)}(R) d_{\rm e} - d_{\rm e} - \epsilon, & bB + t > \frac{BR}{M} \\ 0, & \text{otherwise.} \end{cases} \tag{51}$$

The SNR-exponent is then

$$d^{(r)}(R, d_{\rm e}, d_{\rm peak}) = d^{(\rm r)}(R) \left(1 - \epsilon + d^{(\rm r)}(R) d_{\rm e}\right). \tag{52}$$

The assumption $\pi(\hat{\mathbf{\Omega}}) = 1 + \sum_{b,t,r} \hat{\omega}_{b,t,r}$ requires that $d_{\rm peak} \geq 1 + d^{(\rm r)}(R) d_{\rm e}$.

Collecting the results, and letting $\epsilon \downarrow 0$, the achievable SNR-exponent is

$$\begin{aligned} d^{(r)}&(R, d_{\rm e}, d_{\rm peak}) \\ &= \begin{cases} d^{(\rm r)}(R) d_{\rm peak}, & d_{\rm peak} \leq 1 + d^{(\rm r)}(R) d_{\rm peak} \\ d^{(\rm r)}(R) \left(1 + d^{(\rm r)}(R) d_{\rm e}\right), & d_{\rm peak} > 1 + d^{(\rm r)}(R) d_{\rm peak}. \end{cases} \end{aligned} \tag{53}$$

APPENDIX B
ASYMPTOTIC EXPANSION OF (40)

We would like to study the asymptotic behavior of

$$P_{\rm e}^{(r)} \doteq \int_{\mathcal{O}} \prod_{b,t,r} f(\bar{\omega}_{b,t,r} \,|\, \hat{\omega}_{b,t,r}) f(\hat{\omega}_{b,t,r}) d\bar{\omega}_{b,t,r} \hat{\omega}_{b,t,r} \tag{54}$$

for some set $\mathcal{O}$, where $\bar{\omega}_{b,t,r}$ and $\hat{\omega}_{b,t,r}$ are defined in Appendix A, $f(\hat{\gamma}_{b,t,r})$ is an exponential p.d.f. and $f(\bar{\gamma}_{b,t,r} \,|\, \hat{\gamma}_{b,t,r})$ is a noncentral chi-square p.d.f. with 2 degrees of freedom and noncentral parameter $\frac{2\hat{\gamma}_{b,t,r}}{\sigma_{\rm e}^2} \doteq {\rm SNR}^{-\hat{\omega}_{b,t,r} + d_{\rm e}}$.

Changing variables in $f(\hat{\gamma}_{b,t,r})$ and $f(\bar{\gamma}_{b,t,r}\,|\,\hat{\gamma}_{b,t,r})$ to $\hat{\omega}_{b,t,r}$ and $\bar{\omega}_{b,t,r}$ gives

$$P_{\mathrm{e}}^{(r)}\dot{\le}\int_{\mathcal{O}}\prod_{b,t,r}g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})d\hat{\omega}_{b,t,r}d\bar{\omega}_{b,t,r} \tag{55}$$

where

$$\begin{aligned}g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r}) \triangleq{}& e^{-\mathrm{SNR}^{-\bar{\omega}_{b,t,r}}}e^{-\mathrm{SNR}^{-(\hat{\omega}_{b,t,r}-d_{\mathrm{e}})}}\\ &\times e^{-\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}}I_0\left(\mathrm{SNR}^{\frac{d_{\mathrm{e}}-\bar{\omega}_{b,t,r}-\hat{\omega}_{b,t,r}}{2}}\right)\\ &\times \mathrm{SNR}^{-(\bar{\omega}_{b,t,r}+\hat{\omega}_{b,t,r})}.\end{aligned} \tag{56}$$

For each (b,t,r), define the set

$$\mathcal{A}_{b,t,r}\triangleq\{\hat{\omega}_{b,t,r},\bar{\omega}_{b,t,r}:d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}>0\} \tag{57}$$

and its complement

$$\mathcal{A}_{b,t,r}^{(c)}\triangleq\{\hat{\omega}_{b,t,r},\bar{\omega}_{b,t,r}:d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}\le 0\}. \tag{58}$$

Firstly, consider the region $\mathcal{A}_{b,t,r}$ for some (b,t,r). Then $\mathrm{SNR}^{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}\to\infty$. It follows that [30, Sec. 9.7]

$$I_0\left(\mathrm{SNR}^{\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2}}\right)\doteq e^{\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2}}\mathrm{SNR}^{\frac{-d_{\mathrm{e}}+\hat{\omega}_{b,t,r}+\bar{\omega}_{b,t,r}}{4}}. \tag{59}$$

In this case, grouping the exponent terms inside the integral (55) gives

$$\exp\left(-\mathrm{SNR}^{-\bar{\omega}_{b,t,r}}-\mathrm{SNR}^{-(\hat{\omega}_{b,t,r}-d_{\mathrm{e}})}+\mathrm{SNR}^{\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2}}\right)\exp(-\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}). \tag{60}$$

Noting that

$$\max(-\bar{\omega}_{b,t,r},-(\hat{\omega}_{b,t,r}-d_{\mathrm{e}}))\ge\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2} \tag{61}$$

for any $\hat{\omega}_{b,t,r},\bar{\omega}_{b,t,r}$ with the equality occurring iff $\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}$. Therefore:

- if $\bar{\omega}_{b,t,r}\neq\hat{\omega}_{b,t,r}-d_{\mathrm{e}}$ then

$$-\mathrm{SNR}^{-\bar{\omega}_{b,t,r}}-\mathrm{SNR}^{-(\hat{\omega}_{b,t,r}-d_{\mathrm{e}})}+\mathrm{SNR}^{\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2}}\doteq-\mathrm{SNR}^{\max(-\bar{\omega}_{b,t,r},-(\hat{\omega}_{b,t,r}-d_{\mathrm{e}}))}.$$

  Since we are considering $\mathcal{A}_{b,t,r}$, where $d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}>0$, so $\max(d_{\mathrm{e}}-\hat{\omega}_{b,t,r},-\bar{\omega}_{b,t,r})>0$. Therefore, if $\bar{\omega}_{b,t,r}\neq\hat{\omega}_{b,t,r}-d_{\mathrm{e}}$, the error probability decays exponentially in SNR or equivalently $g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})\doteq 0$.
- if $\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}$, then the condition $d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}>0$ is equivalent to $\hat{\omega}_{b,t,r}<d_{\mathrm{e}}$.

Thus, we can write

$$\begin{aligned}&\int_{\mathcal{O}\cap\mathcal{A}_{b,t,r}}g_{b,t,r}g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})d\bar{\omega}_{b,t,r}d\hat{\omega}_{b,t,r}\\ &\doteq\int_{\mathcal{O}\cap\{\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}<0\}}g_{b,t,r}e^{-\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}}\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}d\hat{\omega}_{b,t,r}\\ &\doteq\int_{\mathcal{O}\cap\{-d_{\mathrm{e}}\le\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}<0\}}g_{b,t,r}\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}d\hat{\omega}_{b,t,r}\end{aligned} \tag{62}$$

where

$$g_{b,t,r}\triangleq\prod_{(b',t',r')\neq(b,t,r)}g(\bar{\omega}_{b',t',r'},\hat{\omega}_{b',t',r'})d\bar{\omega}_{b',t',r'}d\hat{\omega}_{b',t',r'}.$$

Secondly, consider the region $\mathcal{A}_{b,t,r}^{(c)}$, i.e., $d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}\le 0$. In this case, the asymptotic form of the modified Bessel function of the first kind $I_0(x)$ with $x\downarrow 0$ gives

$$I_0\left(\mathrm{SNR}^{\frac{d_{\mathrm{e}}-\hat{\omega}_{b,t,r}-\bar{\omega}_{b,t,r}}{2}}\right)\doteq 1. \tag{63}$$

Thus, it follows from (56) that

$$g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})\doteq\begin{cases}\mathrm{SNR}^{-(\bar{\omega}_{b,t,r}+\hat{\omega}_{b,t,r})}, & \bar{\omega}_{b,t,r}\ge 0\text{ and }\hat{\omega}_{b,t,r}\ge d_{\mathrm{e}}\\ 0, & \text{otherwise.}\end{cases} \tag{64}$$

Collecting the cases in (62) and (64), it follows that:

$$\begin{aligned}&\int_{\mathcal{O}}\prod_{b,t,r}g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})d\bar{\omega}_{b,t,r}d\hat{\omega}_{b,t,r}\\ &\doteq\int_{\bar{\mathcal{O}}}\prod_{(b,t,r):-d_{\mathrm{e}}\le\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}<0}\{\mathrm{SNR}^{-\hat{\omega}_{b,t,r}}d\hat{\omega}_{b,t,r}\}\\ &\quad\times\prod_{(b,t,r):\bar{\omega}_{b,t,r}\ge 0,\hat{\omega}_{b,t,r}\ge d_{\mathrm{e}}}\Big\{\mathrm{SNR}^{-(\bar{\omega}_{b,t,r}+\hat{\omega}_{b,t,r})}\\ &\quad\times d\bar{\omega}_{b,t,r}d\hat{\omega}_{b,t,r}\Big\}\end{aligned} \tag{65}$$

where

$$\bar{\mathcal{O}}\triangleq\mathcal{O}\cap\left\{\bigcap_{b,t,r}\{0\le\hat{\omega}_{b,t,r}<d_{\mathrm{e}},\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}\}\cup\{\hat{\omega}_{b,t,r}\ge d_{\mathrm{e}},\bar{\omega}_{b,t,r}\ge 0\}\right\}. \tag{66}$$

Therefore, for large SNR

$$\int_{\mathcal{O}}\prod_{b,t,r}g(\bar{\omega}_{b,t,r},\hat{\omega}_{b,t,r})d\bar{\omega}_{b,t,r}d\hat{\omega}_{b,t,r}\doteq\mathrm{SNR}^{-d} \tag{67}$$

where

$$d=\inf_{\mathbf{\Omega},\bar{\mathbf{\Omega}}\in\bar{\mathcal{O}}}\left\{\sum_{(b,t,r):-d_{\mathrm{e}}\le\bar{\omega}_{b,t,r}=\hat{\omega}_{b,t,r}-d_{\mathrm{e}}<0}\hat{\omega}_{b,t,r}+\sum_{(b,t,r):\bar{\omega}_{b,t,r}\ge 0,\hat{\omega}_{b,t,r}\ge d_{\mathrm{e}}}\hat{\omega}_{b,t,r}+\bar{\omega}_{b,t,r}\right\}. \tag{68}$$

Appendix C
Proof of Proposition 2

In order to show that the outage exponent is given by (15), we prove that the outage exponent is upper and lower bounded by (15).

A simple upper bound to the outage exponent to the MIMO channel can be obtained by assuming a genie-aided decoder, that knows and subtracts the interference at the receiver. This way, the channel at each block is reduced to a set of N_t noninterfering SIMO channels, resulting in

$$d_\mathrm{out}(R, d_\mathrm{e}, d_\mathrm{peak}) \leq \begin{cases} d_\mathrm{sb}(R) d_\mathrm{peak} & d_\mathrm{peak} \leq 1 + d_\mathrm{sb}(R) d_\mathrm{e}, \\ d_\mathrm{sb}(R)\left(1 + d_\mathrm{sb}(R) d_\mathrm{e}\right) & d_\mathrm{peak} > 1 + d_\mathrm{sb}(R) d_\mathrm{e}. \end{cases} \tag{69}$$

The proof for the SIMO channel is given in [31], and is not reproduced here for the sake of compactness.

As for the lower bound, consider the following power allocation:

$$\boldsymbol{P}_b(\hat{\boldsymbol{H}}) = P(\hat{\boldsymbol{\Gamma}}) \boldsymbol{I}_{N_\mathrm{t}}, \quad b = 1, \ldots, B \tag{70}$$

where $\hat{\boldsymbol{\Gamma}} \in \mathbb{R}^{B \times N_\mathrm{t} \times N_\mathrm{r}}$ is the matrix of power fading gains with entries $\hat{\gamma}_{b,t,r}$.

The input output mutual information of the MIMO block-fading channel is

$$I(P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}) = \frac{1}{B} \sum_{b=1}^{B} I_\mathcal{X}(P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}_b) \tag{71}$$

where assuming equiprobable inputs

$$I_\mathcal{X}(\boldsymbol{H}) = M N_\mathrm{t} - \frac{1}{2^{M N_\mathrm{t}}} \sum_{\boldsymbol{x} \in \mathcal{X}^{N_\mathrm{t}}} \times \mathbb{E}_{\boldsymbol{w}}\left[\log_2\left(\sum_{\boldsymbol{x}' \in \mathcal{X}^{N_\mathrm{t}}} e^{-\|\boldsymbol{H}(\boldsymbol{x}-\boldsymbol{x}')+\boldsymbol{w}\|^2 + \|\boldsymbol{w}\|^2}\right)\right] \tag{72}$$

where the entries of $\boldsymbol{w}$ are drawn independently from the complex circular Gaussian distribution.

The outage probability is

$$P_\mathrm{out}(R) = \Pr\{I(P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}) < R\}. \tag{73}$$

By defining the normalized power fading gains and power allocation rule as in the previous section, we have that

$$\|P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}_b(\boldsymbol{x}-\boldsymbol{x}')+\boldsymbol{w}\|^2 + \|\boldsymbol{w}\|^2 = -\sum_{r=1}^{N_\mathrm{r}}\left\{\left|\sum_{t=1}^{N_\mathrm{t}} \mathrm{SNR}^{\pi(\hat{\boldsymbol{\Gamma}}) - \frac{\varpi_{b,t,r}+d_e}{2}} \times e^{i\theta_{b,t,r}}(x_t - x'_t) + w_r\right|^2 + |w_r|^2\right\} \tag{74}$$

where w_r is the rth entry of $\boldsymbol{w}$. For any $\epsilon > 0$, define $\mathcal{S}_{b,r}^{(\epsilon)}$, $\mathcal{S}_b^{(\epsilon)}$ and κ_b as in Appendix A. Using similar arguments to those in (33), (34), and (35), it follows that:

$$\lim_{\mathrm{SNR}\to\infty}\left|\sum_{r=1}^{N_\mathrm{r}} \mathrm{SNR}^{\pi(\hat{\boldsymbol{\Gamma}}) - \frac{\varpi_{b,t,r}+d_e}{2}} e^{i\theta_{b,t,r}}(x_t - x'_t) + w_r\right|^2 = \infty \tag{75}$$

with probability 1 if there exists $t \in \mathcal{S}_{b,r}^{(\epsilon)}$ such that $x_t \neq x'_t$. Therefore

$$\lim_{\mathrm{SNR}\to\infty} \mathbb{E}_{\boldsymbol{w}}\left[\log_2\left(e^{\|-P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}_b(\boldsymbol{x}-\boldsymbol{x}')+\boldsymbol{w}\|^2+\|\boldsymbol{w}\|^2}\right)\right] \leq \mathbb{E}_{\boldsymbol{w}}\left[\log_2\left(\sum_{\boldsymbol{x}' \in \mathcal{X}^{N_\mathrm{t}}} \mathbb{1}\left\{x'_t = x_t,\ \forall t \in \mathcal{S}_b^{(\epsilon)}\right\}\right)\right] = M(N_\mathrm{t} - \kappa_b) \tag{76}$$

for all $\boldsymbol{x} \in \mathcal{X}^{N_\mathrm{t}}$. Thus, it follows from previous arguments and (72) that

$$\lim_{\mathrm{SNR}\to\infty} I_\mathcal{X}(P(\hat{\boldsymbol{\Gamma}})\boldsymbol{H}_b) \geq M\kappa_b. \tag{77}$$

Therefore, the outage probability is asymptotically upper bounded by

$$P_\mathrm{out}(\mathrm{SNR}, R) \dot{\leq} \Pr\left\{\sum_{b=1}^{B} \kappa_b < \frac{BR}{M}\right\}. \tag{78}$$

In this case, the set corresponding $\mathcal{O}$ (the outage set) is the same as that defined in (39), except for that the $<$ sign is replaced by $\leq$ in (78). Therefore, it follows (with exactly the same arguments in Appendix A) that

$$d_\mathrm{out}(R, d_\mathrm{e}, d_\mathrm{peak}) \geq \begin{cases} d_\mathrm{sb}(R) d_\mathrm{peak} & d_\mathrm{peak} \leq 1 + d_\mathrm{sb}(R) d_\mathrm{e} \\ d_\mathrm{sb}(R)\left(1 + d_\mathrm{sb}(R) d_\mathrm{e}\right) & d_\mathrm{peak} > 1 + d_\mathrm{sb}(R) d_\mathrm{e}. \end{cases} \tag{79}$$

Since the upper bound in (69) and the lower bound in (79) coincide, this concludes the proof of the converse.

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