DIVERSITY PERFORMANCE OF RICEAN MIMO CHANNELS

Rohit U. Nabar [1], *Helmut Bölcskei* [1], *and Arogyaswami J. Paulraj* [2]

[1] Communication Technology Laboratory
Swiss Federal Institute of Technology (ETH) Zürich
ETF E119, Sternwartstrasse 7, 8092 Zürich, Switzerland
Phone: +41-1-6323081, Email: {nabar, boelcskei}@nari.ee.ethz.ch

[2] Information Systems Laboratory, Stanford University
272 Packard, 350 Serra Mall, Stanford, CA 94305, USA
Phone: +1-650-725-8307, Email: apaulraj@stanford.edu

ABSTRACT

In this paper, we assess the impact of real-world propagation conditions on the maximum achievable diversity performance of communication over MIMO channels. This is done by studying the outage behavior of the single-input single-output (SISO) channel induced by the use of Orthogonal Space-Time Block Codes (OSTBCs). For Ricean fading MIMO channels we demonstrate the existence of an SNR-dependent critical rate, R_{crit}, below which signaling with zero outage is possible, and hence the fading channel behaves like an AWGN channel. For SISO channels, R_{crit} is always zero. In the MIMO case, R_{crit} is a simple function of the angle between the vectorized Ricean component of the channel and the subspace spanned by the vectorized Rayleigh fading component.

1. INTRODUCTION

Wireless links are impaired by random fluctuations in signal level known as fading. Diversity provides the receiver with multiple (ideally independent) replicas of the transmitted signal and is therefore a powerful means to combat fading. Spatial (i.e., antenna) diversity techniques are particularly attractive, since they do not incur a loss in transmission time or bandwidth. Space-time codes [1, 2, 3, 4] are capable of extracting spatial diversity gain in systems employing multiple antennas at transmitter and receiver (multiple-input multiple-output or MIMO systems) without requiring channel knowledge in the transmitter. Orthogonal space-time block codes (OSTBCs) [3, 4] yield maximum spatial diversity gain and at the same time decouple the vector detection problem into scalar detection problems, thereby significantly reducing decoding complexity (at the expense of spatial transmission rate).

The performance of any space-time coding scheme depends strongly on the MIMO channel characteristics which in turn depend on antenna characteristics, height and spacing, and scattering richness. The classical i.i.d. Rayleigh frequency-flat fading MIMO channel model [2] assumes that the elements of the matrix channel are i.i.d. zero-mean circularly-symmetric complex Gaussian distributed. Measurements reveal, however, that in practice the MIMO channel deviates significantly from this idealistic behavior [5]. In this paper, we consider a general MIMO channel model that allows Rayleigh or Ricean fading and arbitrary scalar channel gains and correlation between matrix elements.

Contributions. The aim of this paper is to assess the impact of real-world propagation conditions on maximum achievable diversity performance in MIMO channels. OSTBCs convert the MIMO channel into a single-input single-output (SISO) channel with the effective channel gain given by the sum of the squared magnitudes of the complex-valued scalar subchannel gains [4]. All the degrees of freedom in the channel are thus utilized to realize diversity gain, which implies that the ultimate diversity performance of a general MIMO channel can be assessed by studying the performance (in this case, the *outage capacity* [6]) of the effective SISO channel resulting from the application of OSTBCs.

For Ricean fading MIMO channels we demonstrate the existence of a *critical rate*, R_{crit}, below which signaling with *zero outage* is possible, or equivalently the *channel behaves like an AWGN channel*. In the SISO case the critical rate is always zero, whereas in the MIMO case R_{crit} depends on the *angle* between the *vectorized Ricean component* and the *range-space* of *the Rayleigh fading correlation matrix*. Moreover, we show that channels with $R_{crit} > 0$ have a diversity order of ∞, whereas in the case of $R_{crit} = 0$, the diversity order is given by the rank of the fading correlation matrix.

Relation to previous work. We note that the effective channel for OSTBCs resembles the effective channel obtained for *maximal-ratio combining (MRC)* [7, 8], the performance of which has been studied extensively [8]–[11]. Compared to [8]–[11], our analysis is novel in that it reveals the critical importance of the angle between the vectorized Ricean component and the range-space of the Rayleigh fading correlation matrix in determining performance. Moreover, our results establish the presence of a previously unknown critical transmission rate, below which a Ricean MIMO channel (in conjunction with an OSTBC) behaves like an AWGN channel, and above which it appears fading.

Organization. The remainder of this paper is organized as follows. In Section 2, we introduce the MIMO channel model and the associated signal model for OSTBCs. In Section 3 we review outage capacity performance of OSTBCs. Section 4 derives a power series expansion for the cumulative distribution function (cdf) of the squared Frobenius norm of the MIMO channel matrix. In Section 5, we establish the existence of a critical rate and provide expressions for the diversity order of Ricean fading MIMO channels. We present numerical results in Section 6, and conclusions in Section 7.

Notation. The superscript ^{H} stands for conjugate transposition. $\mathcal{E}$ denotes the expectation operator. $\mathbf{0}_{m,n}$ stands for the $m \times n$ all-zeros matrix. $\mathbf{I}_m$ denotes the $m \times m$ identity matrix. For an $m \times n$ matrix $\mathbf{A} = [\mathbf{a}_1 \ \mathbf{a}_2 \ \ldots \ \mathbf{a}_n]$, we define the $mn \times 1$ vector $\text{vec}(\mathbf{A}) = [\mathbf{a}_1^T \ \mathbf{a}_2^T \ \ldots \ \mathbf{a}_n^T]^T$. $\|\mathbf{A}\|_F = \sqrt{\sum_{i,j} |[\mathbf{A}]_{i,j}|^2}$, $r(\mathbf{A})$,

$\mathcal{R}(\mathbf{A})$, and $\mathcal{N}(\mathbf{A})$, denote the Frobenius norm, rank, range-space and null-space, respectively, of the matrix $\mathbf{A}$. $u(y)$ stands for the unit-step function defined as $u(y) = 1$ for $y \geq 0$ and 0 otherwise. A circularly symmetric complex Gaussian random variable is a random variable $Z = X + jY \sim \mathcal{CN}(0, \sigma^2)$, where X and Y are i.i.d. $\mathcal{N}(0, \frac{\sigma^2}{2})$.

2. CHANNEL AND SIGNAL MODEL

In this section, we introduce the MIMO channel model used throughout the paper followed by a brief description of the signal model associated with OSTBCs.

2.1. General MIMO channel model

We consider a frequency-flat fading MIMO channel with M_T transmit and M_R receive antennas. The corresponding $M_R \times M_T$ random channel matrix $\mathbf{H} = \overline{\mathbf{H}} + \widetilde{\mathbf{H}}$ is decomposed into the sum of a fixed (possibly line-of-sight (LOS)) component $\overline{\mathbf{H}} = \mathcal{E}\{\mathbf{H}\}$ and a variable (or scattered) component $\widetilde{\mathbf{H}}$. In the case of pure Rayleigh fading $\overline{\mathbf{H}} = \mathbf{0}_{M_R,M_T}$, whereas in the case of Ricean fading $\overline{\mathbf{H}} \neq \mathbf{0}_{M_R,M_T}$. Throughout the remainder of this paper, we let $N = M_T M_R$ and apply the power normalization $\mathcal{E}\{\|\mathbf{H}\|_F^2\} = \|\overline{\mathbf{H}}\|_F^2 + \mathcal{E}\{\|\widetilde{\mathbf{H}}\|_F^2\} = N$. Furthermore, we assume that the channel is block fading [12] so that $\mathbf{H}$ remains constant over $T \geq M_T$ symbol periods and changes in an independent fashion from block to block. The elements of $\widetilde{\mathbf{H}}$ are circularly symmetric complex Gaussian random variables. With large antenna spacing, rich scattering in the propagation environment and all antenna elements employing identical polarization, the scalar subchannels of $\widetilde{\mathbf{H}}$ can furthermore be assumed i.i.d. In practice, however, these conditions are hardly met, so that the elements of $\widetilde{\mathbf{H}}$ will be correlated with possibly different variances resulting from power/gain imbalance and/or the use of different antenna polarizations. Defining $\widetilde{\mathbf{h}} = \text{vec}(\widetilde{\mathbf{H}})$, the statistics of $\widetilde{\mathbf{H}}$ are characterized by the $N \times N$ correlation matrix $\mathbf{R} = \mathcal{E}\left\{\widetilde{\mathbf{h}}\widetilde{\mathbf{h}}^H\right\}$ with eigendecomposition $\mathbf{R} = \mathbf{U}\mathbf{\Sigma}\mathbf{U}^H$, where $\mathbf{\Sigma} = \text{diag}\{\sigma_j\}_{j=1}^N$ with $\sigma_j \geq \sigma_{j+1}$ $(j = 1, 2, ..., N-1)$. Furthermore, we set $\mathbf{h} = \text{vec}(\mathbf{H})$ and $\overline{\mathbf{h}} = \text{vec}(\overline{\mathbf{H}})$. Note that $\overline{\mathbf{h}}$ and $\mathbf{R}$ completely characterize the statistics of the Ricean MIMO channel. The classical i.i.d. Rayleigh fading MIMO channel is recovered for $\overline{\mathbf{h}} = \mathbf{0}_{N,1}$ and $\mathbf{R} = \mathbf{I}_N$.

2.2. Signal model

The input-output relation is given by

$$\mathbf{y} = \sqrt{\frac{E_s}{M_T}}\mathbf{H}\mathbf{s} + \mathbf{n},$$

where $\mathbf{y}$ denotes the $M_R \times 1$ received signal vector, E_s is the total average energy available at the transmitter over one symbol period, $\mathbf{s}$ is the $M_T \times 1$ transmit signal vector, and $\mathbf{n}$ is $M_R \times 1$ spatio-temporally white noise with $\mathcal{E}\{\mathbf{n}\mathbf{n}^H\} = N_o \mathbf{I}_{M_R}$. We impose the transmit power constraint $\text{Tr}(\mathcal{E}\{\mathbf{s}\mathbf{s}^H\}) = M_T$. Throughout the paper, we assume that the channel $\mathbf{H}$ is unknown at the transmitter and perfectly known at the receiver. Finally, we note that the use of OSTBCs combined with appropriate processing at the receiver [3, 4] turns the matrix channel $\mathbf{H}$ into a scalar channel with effective channel gain $\|\mathbf{H}\|_F^2$. The corresponding effective SISO input-output relation is consequently given by

$$y = \sqrt{\frac{E_s}{M_T}}\|\mathbf{H}\|_F^2 s + n, \tag{1}$$

where y denotes the scalar processed received signal, s is the scalar transmitted signal, and n is $\mathcal{CN}(0, \|\mathbf{H}\|_F^2 N_o)$ white noise.

3. OUTAGE CAPACITY OF OSTBCs

Due to the scalar nature of the effective channel induced by OSTBCs [3, 4], assuming a scalar Gaussian code book, the corresponding mutual information is given by

$$I = r_c \log_2\left(1 + \frac{\rho}{M_T}\|\mathbf{H}\|_F^2\right) \quad \text{bps/Hz}, \tag{2}$$

where $\rho = E_s/N_o$ is the per-antenna receive signal-to-noise ratio (SNR) and $r_c \leq 1$ denotes the spatial rate of the space-time block code as defined in [4].

Since $\mathbf{H}$ is random, the mutual information I will be a random variable. The outage probability corresponding to transmission rate R is defined as $P_{out}(R) = P(I \leq R)$ [6, 12]. Equivalently, one can characterize the outage behavior by specifying the $q\%$ outage capacity $C_{out,q}$ as the capacity that is guaranteed for $(100 - q)\%$ of the channel realizations, i.e., $P(I \leq C_{out,q}) = q\%$.

For the case where codewords span only one fading block, the outage probability can be related to packet error rate (PER) as follows. Since the channel is drawn randomly according to a given fading distribution, there will always be a non-zero probability that a given transmission rate (no matter how small) is not supported by the channel. Assuming that the transmitted codeword (packet) is decoded successfully if the transmission rate is at or below the mutual information of the given channel realization and declaring a decoding error otherwise, the outage probability equals the PER. This leads to the notion of a rate-dependent diversity order as defined in [13]

$$d(R) = -\lim_{\rho\to\infty} \frac{\log P_{out}(R)}{\log \rho}. \tag{3}$$

Clearly, the statistics of $\|\mathbf{H}\|_F^2$ (which in turn depend on the channel conditions) will have a significant influence on the PER and hence the (rate-dependent) diversity order.

4. DERIVATION OF THE CDF OF $\|\mathbf{H}\|_F^2$

In the previous section we have seen that specification of the diversity performance through PER requires computation of the cdf $F(y)$ of $\|\mathbf{H}\|_F^2$. Modifying the approach described in [14] to apply to the complex-valued case, we can derive a power series expansion for $F(y)$ given by [15]

$$F(y) = \sum_{k=0}^{\infty} c_k \frac{(y - C)^{r(\mathbf{R})+k}}{(r(\mathbf{R}) + k)!} u(y - C), \tag{4}$$

where $C = \|\overline{\mathbf{H}}\|_F^2 - \sum_{j=1}^{r(\mathbf{R})} \frac{|b_j|^2}{\sigma_j}$ and b_j is the j-th element of $\mathbf{b} = \mathbf{\Sigma}^{1/2}\mathbf{U}^H\overline{\mathbf{h}}$. The coefficients of the power series can be determined recursively using [14, 15]

$$c_k = \frac{1}{k}\sum_{r=0}^{k-1} d_{k-r}\, c_r, \quad \text{for} \quad k \geq 1,$$

where

$$c_0 = \left(\prod_{j=1}^{r(\mathbf{R})} \frac{1}{\sigma_j}\right) \exp\left(-\sum_{j=1}^{r(\mathbf{R})} \frac{|b_j|^2}{\sigma_j^2}\right),$$

and

$$d_0 = -\sum_{j=1}^{r(\mathbf{R})} \ln(\sigma_j) - \sum_{j=1}^{r(\mathbf{R})} \frac{|b_j|^2}{\sigma_j^2}.$$

The truncation analysis in [16] can readily be extended to the complex-valued case to derive bounds on the residual error associated with summing a finite number of terms in the power series expansion (4). Specifically, denoting the truncation error that results from using only the first term in the power series expansion (4) as $E(y)$, it follows from [16, Eq. (121)] that $E(y) \propto y^{(r(\mathbf{R})+1)} e^{\frac{y}{\beta}}$ (with β arbitrarily chosen to satisfy $0 < \beta < \sigma_{r(\mathbf{R})}$) and hence

$$\lim_{y \to 0} E(y) = 0.$$

The convergence properties of the power series expansion in the low outage regime will be used in the next section to analytically characterize PER-based diversity performance.

5. CRITICAL TRANSMISSION RATE AND DIVERSITY ORDER IN RICEAN MIMO CHANNELS

In this section, we study the impact of propagation conditions on PER as defined in Section 3. More specifically, employing the power series expansion in (4) we compute the outage related diversity order $d(R)$ as defined in (3) as a function of the propagation parameters. Moreover, the analysis presented in this section establishes the existence of a critical rate R_{crit}, below which Ricean fading channels behave like AWGN channels in the sense that signaling with zero outage is possible. For rates above R_{crit}, the Ricean channel behaves like a Rayleigh fading channel. Interestingly, it can be shown that R_{crit} is a simple function of the angle between $\overline{\mathbf{h}}$ and $\mathcal{R}(\mathbf{R})$, denoted by $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R}))$.

Our analysis is for the high-SNR case (i.e., $\rho \gg 1$) which allows us to approximate the cdf of $\|\mathbf{H}\|_F^2$ by retaining the first term in the power series expansion (4)

$$\begin{aligned} P_{out}(R) \approx\ & c_0 \left(\frac{\left(2^{\frac{R}{r_c}} - 1\right) M_T}{\rho} - C \right)^{r(\mathbf{R})} (r(\mathbf{R})!)^{-1} \times \\ & u\left(\frac{\left(2^{\frac{R}{r_c}} - 1\right) M_T}{\rho} - C \right), \end{aligned} \quad (5)$$

where C was defined in (4). We shall next distinguish the cases $C = 0$ and $C > 0$. The case $C < 0$ is excluded since

$$C = \overline{\mathbf{h}}^H \mathbf{U} \underbrace{\begin{bmatrix} \mathbf{0}_{r(\mathbf{R}),r(\mathbf{R})} & \mathbf{0}_{r(\mathbf{R}),N-r(\mathbf{R})} \\ \mathbf{0}_{N-r(\mathbf{R}),r(\mathbf{R})} & \mathbf{I}_{N-r(\mathbf{R})} \end{bmatrix}}_{\mathbf{A}} \mathbf{U}^H \overline{\mathbf{h}} \geq 0. \quad (6)$$

Recalling that $\mathbf{U}$ contains the eigenvectors of $\mathbf{R}$, it follows that $\mathbf{UA}$ spans $\mathcal{N}(\mathbf{R})$, while $\mathbf{U}(\mathbf{I}_N - \mathbf{A})$ spans $\mathcal{R}(\mathbf{R})$. We can now conclude that equality in (6) is achieved in either of the following cases – (i) $\overline{\mathbf{h}} \neq \mathbf{0}_{N,1}$ and $r(\mathbf{R}) = N$, (ii) $\overline{\mathbf{h}} = \mathbf{0}_{N,1}$ and $\mathbf{R}$ arbitrary, (iii) $\overline{\mathbf{h}} \neq \mathbf{0}_{N,1}$, $r(\mathbf{R}) < N$ and $\overline{\mathbf{h}}$ lies completely in $\mathcal{R}(\mathbf{R})$.

For $C = 0$, the unit-step function in (5) will be equal to 1 for all rates R so that

$$\begin{aligned} \log P_{out}(R) =\ & \log c_0 + r(\mathbf{R}) \log \left(\left(2^{\frac{R}{r_c}} - 1\right) M_T \right) - \\ & r(\mathbf{R}) \log \rho - \log(r(\mathbf{R})!). \end{aligned}$$

Invoking (3) we find that for a fixed transmission rate R

$$d(R) = r(\mathbf{R}),$$

which immediately implies that in the case of pure Rayleigh fading (i.e., $\overline{\mathbf{h}} = \mathbf{0}_{N,1}$) the diversity order is given by $d(R) = r(\mathbf{R})$. In the Ricean case, the situation is more complicated as both $C = 0$ and $C > 0$ are possible.

Let us proceed with the case $C > 0$. Investigating the argument of the unit-step function in (5) we obtain

$$P_{out}(R) \begin{cases} = 0, & R < R_{crit} \\ \approx c_0 \dfrac{\left(\frac{\left(2^{\frac{R}{r_c}} - 1\right) M_T}{\rho} - C \right)^{r(\mathbf{R})}}{r(\mathbf{R})!}, & R \geq R_{crit} \end{cases}, \quad (7)$$

where $R_{crit} = r_c \log_2 \left(1 + \frac{C\rho}{M_T}\right)$. This result points at an interesting behavior. For fixed (SNR-independent) transmission rate R and high enough SNR ρ (so that $R < R_{crit}$), signaling with zero outage is possible, and the channel behaves like an AWGN channel. Consequently, we obtain $d(R) = \infty$. Interestingly, up to the pre-log r_c, the critical rate R_{crit} is the capacity of a SISO AWGN channel with SNR $= \frac{C\rho}{M_T}$. Note that while (7) presents the outage probability for high SNR, it follows from (4) (cf. the argument of the unit-step function) that the presence of a critical rate can be established at any SNR and without invoking any approximation for $P_{out}(R)$.

We can summarize our findings by noting that for fixed transmission rate R

$$d(R) = \begin{cases} \infty, & C > 0 \\ r(\mathbf{R}), & C = 0 \end{cases}. \quad (8)$$

This result has a nice physical interpretation: Let us start by investigating the SISO case where $h = \overline{h} + \widetilde{h}$ and (6) reduces to $C = \gamma \left|\overline{h}\right|^2$ with

$$\gamma = \begin{cases} 0, & K < \infty \\ 1, & K = \infty \end{cases},$$

where $K = \frac{|\overline{h}|^2}{\mathcal{E}\left\{|\widetilde{h}|^2\right\}}$ denotes the Ricean K-factor [17] of the SISO channel. Employing (8) we can immediately conclude that $d(R) = 1$ for $K < \infty$ and $d(R) = \infty$ if $K = \infty$. Equivalently, this result says that the diversity order equals 1 as long as there is a Rayleigh fading component in the channel and the diversity order becomes ∞ for an AWGN channel.

This observation can be generalized to arbitrary MIMO channels with $N = M_T M_R$. The realizations of the N-dimensional random vector $\mathbf{h} = \overline{\mathbf{h}} + \widetilde{\mathbf{h}}$ span a subspace which depends on $\overline{\mathbf{h}}$ and the subspace spanned by the realizations of $\widetilde{\mathbf{h}}$ and hence specified by $\mathbf{R}$. Now, in the case where $\overline{\mathbf{h}}$ lies entirely in the range-space of $\mathbf{R}$ (and hence the subspace spanned by the realizations of $\widetilde{\mathbf{h}}$) all the dimensions "excited" by $\mathbf{h}$ will have a Rayleigh fading component so that, using our result above for the SISO case, the diversity order is simply the number of dimensions excited by $\mathbf{h}$ or equivalently $d(R) = r(\mathbf{R})$. In the case where $\mathbf{h}$ has non-zero projections onto $\mathcal{N}(\mathbf{R})$, we have at least one dimension which is purely AWGN and hence we get $d(R) = \infty$. Equivalently, we can conclude that $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R})) \neq 0$ implies a diversity order of ∞, whereas $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R})) = 0$ results in $d = r(\mathbf{R})$. Furthermore, we note that $R_{crit} = 0$ if $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R})) = 0$ and $R_{crit} > 0$ if $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R})) \neq 0$. Consequently, $R_{crit} = 0$ for a SISO fading channel.

6. NUMERICAL EXAMPLE

For the sake of simplicity, we consider a system with two transmit antennas and a single receive antenna employing the Alamouti scheme

($r_c = 1$). The fixed and variable channel components are given by

$$\overline{\mathbf{H}} = \sqrt{\frac{K}{1+K}}\,[1 \quad 1]\,, \qquad \widetilde{\mathbf{H}} = \sqrt{\frac{1}{1+K}}\,[\widetilde{g}_{1,1} \quad \widetilde{g}_{1,2}]\,,$$

where $K \geq 0$ denotes the Ricean K-factor. Furthermore, we define the following transmit correlation coefficient

$$t = \frac{\mathcal{E}\{\widetilde{g}_{1,1}\,\widetilde{g}_{1,2}^*\}}{\sqrt{\mathcal{E}\{|\widetilde{g}_{1,1}|^2\}\mathcal{E}\{|\widetilde{g}_{1,2}|^2\}}}.$$

Unless specified otherwise, we set $\mathcal{E}\{|\widetilde{g}_{1,1}|^2\} = \mathcal{E}\{|\widetilde{g}_{1,2}|^2\} = 1$.

This example serves to demonstrate the impact of $\angle(\overline{\mathbf{h}}, \mathcal{R}(\mathbf{R}))$ on R_{crit} and outage performance. We consider two different channels, $\mathbf{H}_1$ and $\mathbf{H}_2$, having different fixed components, $\overline{\mathbf{H}}_1 = [1 \quad 1]$ and $\overline{\mathbf{H}}_2 = [1 \quad -1]$, respectively, but the same fading components. For $K = 2$ and $R = 2$bps/Hz, Fig. 1 shows the empirically (through Monte Carlo simulation) calculated PER for the two channels for $t = 0$ and $t = 1$. In the uncorrelated case $t = 0$, we have $C = 0$ and consequently $R_{crit} = 0$ for both channels. Fig. 1 indeed shows that the two channels yield equal performance and exhibit Rayleigh fading behavior with $d = 2$ as suggested by (8). In the fully correlated case $t = 1$, $R_{crit} = 0$ for Channel 1, which combined with $r(\mathbf{R}) = 1$ yields a Rayleigh fading behavior as seen in Fig. 1. Channel 2, however, has a non-zero critical rate for $t = 1$ given by $R_{crit} = \log_2\left(1 + \frac{2\rho}{3}\right)$, and hence behaves like an AWGN channel for SNRs above 6.53dB. (The performance of an AWGN channel with $\|\mathbf{H}\|_F^2 = 2$ is shown for comparison.)

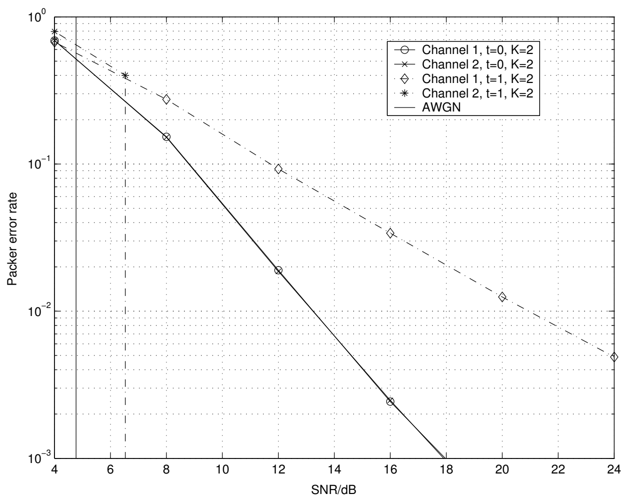

Fig. 1. *Impact of the angle between* $\overline{\mathbf{h}}$ *and* $\mathcal{R}(\mathbf{R})$ *on PER performance. Both channels perform equally well under independent fading.*

7. CONCLUSIONS

We demonstrated the presence of an SNR-dependent critical transmission rate, R_{crit}, in Ricean fading MIMO channels below which signaling with zero outage is possible. For SISO channels, R_{crit} is always zero whereas for MIMO channels, R_{crit} depends on the angle between the vectorized Ricean component of the channel and the subspace spanned by the realizations of the vectorized Rayleigh fading component.

8. REFERENCES

[1] J. Guey, M. P. Fitz, M. R. Bell, and W. Kuo, "Signal design for transmitter diversity wireless communication systems over Rayleigh fading channels," in *Proc. IEEE VTC*, Atlanta, GA, Apr./May 1996, vol. 1, pp. 136–140.

[2] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Trans. Inf. Theory*, vol. 44, no. 2, pp. 744–765, March 1998.

[3] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Comm.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[4] V. Tarokh, H. Jafarkhani, and A.R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, July 1999.

[5] D. S. Baum, D. Gore, R. Nabar, S. Panchanathan, K. V. S. Hari, V. Erceg, and A. J. Paulraj, "Measurement and characterization of broadband MIMO fixed wireless channels at 2.5 GHz," in *Proc. IEEE ICPWC*, Hyderabad, India, Dec. 2000, pp. 203–206.

[6] L. H. Ozarow, S. Shamai, and A. D. Wyner, "Information theoretic considerations for cellular mobile radio," *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, pp. 359–378, May 1994.

[7] W. C. Jakes, *Microwave Mobile Communications*, Wiley, New York, NY, 1974.

[8] M. K. Simon and M. S. Alouini, *Digital communication over fading channels: A unified approach to performance analysis*, Wiley, New York, NY, 2000.

[9] Y. Ko, M. S. Alouini, and M. K. Simon, "Outage probability of diversity systems over generalized fading channels," *IEEE Trans. Comm.*, vol. 48, no. 11, pp. 1783–1787, Nov. 2000.

[10] M. S. Alouini, A. Abdi, and M. Kaveh, "Sum of gamma variates and performance of wireless communication systems over Nakagami-fading channels," *IEEE Trans. Veh. Tech.*, vol. 50, no. 6, pp. 1471–1480, Nov. 2001.

[11] Z. Wang and G. B. Giannakis, "A simple and general parameterization quantifying performance in fading channels," *IEEE Trans. Comm.*, vol. 51, no. 8, pp. 1389–1398, Aug. 2003.

[12] E. Biglieri, J. Proakis, and S. Shamai, "Fading channels: Information-theoretic and communications aspects," *IEEE Trans. Inf. Theory*, vol. 44, no. 6, pp. 2619–2692, Oct. 1998.

[13] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 5, pp. 1073–1096, May 2003.

[14] A. M. Mathai and S. B. Provost, *Quadratic Forms in Random Variables*, Marcell Dekker, Inc., New York, NY, 1992.

[15] R. U. Nabar, H. Bölcskei, and A. J. Paulraj, "Diversity and outage performance of Ricean MIMO channels," *IEEE Trans. Wireless Comm.*, Dec. 2003, submitted.

[16] S. Kotz, N. L. Johnson, and D. W. Boyd, "Series representations of distributions of quadratic forms in normal random variables II: Non-central case," *Ann. Math. Stat.*, vol. 38, pp. 838–848, 1967.

[17] G. Stüber, *Principles of Mobile Communication*, Kluwer, Norwell, MA, 1996.