The Rate-Diversity Trade-Off for Linear Space-Time Codes

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***Abstract* — We study the relative impact of rate and raw diversity order on the capacity and performance of linear space-time codes. Outage capacity is not directly affected by raw diversity order, but it is strongly impacted by the rate of a space-time code. Specifically, if a linear space-time code operating over a t-input, r-output Rayleigh-fading channel has rate $R < \min(t, r)$, we show that it achieves at most a fraction $R / \min(t, r)$ of the channel's outage capacity at high SNR. In the absence of outer codes, the performance of the space-time code depends strongly on both the rate and the raw diversity order. Since low complexity space-time codes with both high rate and high raw diversity order are hard to find, there is a trade-off between rate and raw diversity order. We propose a heuristic rule of thumb: start with a rate equal to $\min(t, r)$ and lower it until a space-time code with raw diversity order of $\min(tr, 4)$ can be found. In particular, when there are 4 or more receive antennas, the rate should be $\min(t, r)$. Simulation results for an 8×8 Rayleigh channel show that the rate-8, diversity-8 V-BLAST encoder outperforms a rate-4, diversity-16 Alamouti-based GLST [1] encoder by 7 dB with ML decoding.**

I. Introduction

Space-time codes offer protection against deep fades by carefully introducing spatial redundancy into the transmitted signal. The performance of a space-time code is strongly impacted by its *rate*, defined as the number of information symbols conveyed per signaling interval, and its *raw diversity order*, as determined by the rank criterion [2]. The rate measures the amount of redundancy introduced by the space-time code, and the raw diversity order quantifies the effectiveness of the redundancy. This paper studies the impact of the choice of these two parameters on the performance of space-time codes, with and without an outer code.

Outage capacity is a useful measure of performance when the space-time code is complemented by an outer error-correction code. In [3] and [4] it was shown that a space-time code with rate less than $\min(t, r)$ suffers a non-zero loss in outage capacity. However, the amount of capacity lost was not quantified. In [5], it was shown that an orthogonal block code [6] with rate $R < 1$ and one receiver antenna achieves only a fraction R of the channel's outage capacity. The capacity penalty of more general space-time codes, operating over channels with multiple receive antennas, was posed as an open question. We provide a partial answer to that question. By studying the slope of high-SNR capacity asymptotes, we show that at high SNR, a linear space-time code with rate R less than $\min(t, r)$ achieves at most a fraction $R / \min(t, r)$ of the channel's outage capacity.

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Although the rate of a space-time code has a strong impact on outage capacity, its raw diversity order does not. This is because the rank criterion [2] for computing the raw diversity order assumes that the inputs to the space-time code are independent. The presence of an outer code introduces dependency in the inputs that makes the *achievable* diversity order higher than the raw diversity order. We show qualitatively that the zero offset of the outage capacity asymptotes increases with the achievable diversity order.

When complexity and latency considerations prevent the use of strong outer codes, outage capacity is no longer a meaningful performance metric. Without an outer code, both the raw diversity order and the rate are important determinants of performance; a high raw diversity order reduces error rates by providing diversity gain, while a high rate enables the use of small constellations, thus increasing the minimum distance and providing coding gain [2]. While it is both desirable and theoretically possible to use space-time codes with high raw diversity order and high rate, low complexity codes with both these properties are known only for a few MIMO channels [6]. High diversity order often implies low rate, and there is thus a trade-off between the two conflicting goals. The key question is this: which is better, a high-rate low-diversity space-time code, or a low-rate high-diversity space-time code? More specifically, for a given target error probability and information rate, what combination of rate and diversity order should one choose to minimize the required SNR?

We provide a heuristic rule of thumb in this paper: One should start with a rate equal to $\min(t, r)$ and reduce the rate until one is able to find a space-time code with a raw diversity order of $\min(tr, 4)$. In particular, if there are 4 or more receive antennas, there is already enough raw diversity order even without additional transmit diversity, and one should use a code with rate $\min(t, r)$. This heuristic rule is supported by simulation results for 32 bits/s/Hz over an 8×8 Rayleigh fading channel, where a high-rate low-diversity code is shown to outperform a low-rate high-diversity code by 7 dB.

In Section II, we present some background, and establish the relationship between outage capacity and diversity order of MIMO channels. In Section III, we discuss the outage capacity of space-time codes, with an example showing the effect of rate and achievable diversity order on the outage capacity. In Section IV, we discuss the rate-diversity trade-off in the absence of outer codes, and propose a heuristic rule of thumb supported by simulation results. Section V summarizes the conclusions from this paper.

II. The Outage Capacity of MIMO Channels

A t-transmit, r-receive antenna static wireless MIMO channel is modeled as

$$\mathbf{y}_k = \mathbf{H}\mathbf{x}_k + \mathbf{n}_k \, , \tag{1}$$

where $\mathbf{x}_k$ is the $t \times 1$ channel input and $\mathbf{y}_k$ the $r \times 1$ channel output at time k. The noise $\mathbf{n}_k$ is spectrally and temporally white, so that $\mathrm{E}[\mathbf{n}_{k+l}\mathbf{n}_k{}^*] = \delta_l N_0 \mathbf{I}_r$. The entries of the $r \times t$ Rayleigh-fading channel matrix $\mathbf{H}$ are independent, circularly symmetric, unit-variance Gaussian random variables. We assume that $\mathbf{H}$ is unknown to the transmitter, but known to the receiver. The SNR S is defined as the ratio of the average received signal power to the average noise power at any receive antenna, namely $S = \mathrm{E}[\| \mathbf{x}_k \|^2] / N_0$.

The capacity of the MIMO channel for any particular $\mathbf{H}$, constrained by the transmitter's ignorance of $\mathbf{H}$, is [7]

$$I_S(\mathbf{H}) = \log\det\left(\mathbf{I}_r + \frac{S}{t}\mathbf{H}\mathbf{H}^*\right). \tag{2}$$

The available capacity $I_S(\mathbf{H})$ is a random variable unknown to the transmitter. If it falls below the transmit data rate R_b, error probability cannot be made zero by any code. This event is called an *outage*. Let $F_S(x)$ denote the cumulative distribution function of $I_S(\mathbf{H})$ for an SNR S. The outage probability is the probability that an outage occurs, and is clearly equal to $F_S(R_b)$. As the SNR increases, the outage probability decreases. The *diversity order* d quantifies the rate at which this decrease occurs, as defined by the limit:

$$d = -\lim_{S \to \infty} \frac{\log F_S(R_b)}{\log S} \, . \tag{3}$$

Graphically, the diversity order measures the asymptotic slope of outage probability versus SNR plotted on a log-log scale. $F_S(x)$ is known for Rayleigh fading channels [7], and can be used to prove the following theorem [8].

Theorem 1. The diversity order of a t-transmit, r-receive antenna Rayleigh-fading channel is

$$d = tr \, . \tag{4}$$

An alternative definition of diversity order based on the *pairwise* error probability also leads to the value tr for the maximum possible diversity order for codes operating over the Rayleigh channel [2]. The agreement between the two definitions is not surprising since the outage probability bounds the lowest achievable error probability.

Instead of fixing data rate and varying the SNR to obtain different performance levels, one could fix the target outage probability and try to achieve the maximum possible data rate. As the data rate R_b increases, the outage probability $F_S(R_b)$ increases. For a given SNR S, the maximum data rate at which the outage probability is still below a target value p_o is called the *outage capacity* for that value of p_o, and is defined by:

$$C(S, p_o) = \sup\{R_b \colon F_S(R_b) < p_o\} \, .$$

Analogous to diversity order, we define *capacity order* m by the limit:

$$m = \lim_{S \to \infty} \frac{\log C(S, p_o)}{\log S} \, , \tag{5}$$

which is the asymptotic rate at which outage capacity increases with log SNR. The following result relates capacity order to the number of transmit and receive antennas [8].

Theorem 2. The capacity order of a t-transmit, r-receive antenna Rayleigh fading channel is

$$m = \min(t, r) \, . \tag{6}$$

This result should be contrasted with [9], where the asymptotic slope of the average capacity (instead of outage capacity) is also shown to be $\min(t, r)$.

From (6), the high-SNR asymptote of the capacity versus log SNR plot is a straight line with slope m, namely $\overline{C} = m\log S + \alpha(p_o)$, where the zero offset $\alpha(p_o)$ is a function of the target outage probability p_o. Although the diversity order does not affect the slope, it does affect the offset. We will now show that among two channels with the same capacity order, the one with the higher diversity order has the larger zero offset for small p_o.

Consider the sketch in Fig. 1, which shows capacity and outage probability asymptotes at high SNR. The upper plot shows the outage capacity asymptotes for outage probabilities p and $q < p$. The lower plot shows the asymptotic plot of log outage probability versus log SNR for a data rate R_b in the high SNR region. By the definition of capacity and diversity orders, the slopes of the lines in the upper and lower plots are m and $-d$, respectively. Now, from the sketch, $\Delta z / \Delta x = d$, and $\Delta y / \Delta x = m$, giving $\Delta y = \Delta z m / d$. But since $\Delta y = \alpha(p) - \alpha(q)$ and $\Delta z = \log(p) - \log(q)$, solving for $\alpha(q)$ yields:

$$\alpha(q) = f(p) + \log(q)\, m / d \, , \tag{7}$$

where $f(p) = \alpha(p) - \log(p)\, m / d$ is independent of q. From (7), the rate at which $\alpha(q)$ decreases with q is inversely proportional to the diversity order d. Clearly, for a sufficiently small q, a higher-diversity channel will have a higher offset than a lower-diversity channel.

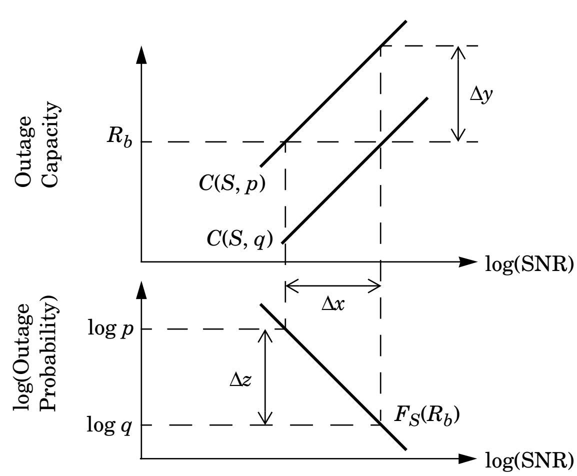

Fig. 1. Sketch of outage capacity and outage probability asymptotes.

III. Outage Capacity of Linear Space-Time Codes

It is common for a transmitter to use a concatenated coding scheme consisting of an outer code feeding complex symbols to an inner space-time code. For example, the outer code could be a binary turbo code feeding BPSK symbols to an inner Alamouti code. The purpose of the space-time code is to offer protection against deep fades by carefully introducing redundancy across space and time. The rate of the space-time code, defined as the number of complex symbols it encodes per signaling interval, measures the amount of redundancy introduced. The effectiveness of the redundancy is measured by the raw diversity order of the space-time code with uncoded complex inputs, and is determined by the rank criterion [2].

The combination of the space-time code and the underlying MIMO fading channel forms an *effective* channel as seen by an outer encoder and the decoder at the receiver. In this section, we study the outage capacity of this effective channel. With some abuse of notation, we will also call this quantity the outage capacity of the space-time code itself. In particular, we will show that the outage capacity is not very sensitive to the raw diversity order of the space-time code, but depends strongly on the rate.

Consider a rate-K/N space-time code which takes in blocks of K complex symbols and uses them to generate N blocks of $t \times 1$ complex vectors. We restrict attention to *linear* space-time codes, which obtain each complex output-symbol by some linear combination of the K inputs and their complex conjugates. Following [7], we define the transformations

$$\hat{\mathbf{x}} = \begin{bmatrix} \mathrm{Re}\{\mathbf{x}\} \\ \mathrm{Im}\{\mathbf{x}\} \end{bmatrix}, \text{ and } \hat{\mathbf{A}} = \begin{bmatrix} \mathrm{Re}\{\mathbf{A}\} & \mathrm{Im}\{\mathbf{A}\} \\ -\mathrm{Im}\{\mathbf{A}\} & \mathrm{Re}\{\mathbf{A}\} \end{bmatrix}, \tag{8}$$

for complex vectors $\mathbf{x}$ and matrices $\mathbf{A}$. Let the j^{th} input block be $\mathbf{u}_j = [u_j(1), \ldots u_j(K)]^T$. Stacking the N $t \times 1$ channel-input vectors $\mathbf{x}_{j,1}, \mathbf{x}_{j,2}, \ldots \mathbf{x}_{j,N}$ in block j one below the other, we get the composite $Nt \times 1$ output vector $\mathbf{x}_j$. A complex linear encoder obtains $\mathbf{x}_j$ by [3]:

$$\hat{\mathbf{x}}_j = \mathbf{L}_j \hat{\mathbf{u}}_j \tag{9}$$

for some matrix $\mathbf{L}_j$. In (9), we have allowed for the possibility that the encoder is time-variant, with the assumption that $\mathbf{L}_j$ be chosen independently and uniformly for each j. Stacking the N $r \times 1$ channel output vectors, we get the composite channel output vector $\mathbf{y}_j$, which is related to $\mathbf{x}_j$ by

$$\mathbf{y}_j = \begin{bmatrix} \mathbf{H} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{H} & \mathbf{0} \ddots & \vdots \\ \vdots & \mathbf{0} & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{H} \end{bmatrix} \mathbf{x}_j + \mathbf{n}_j , \tag{10}$$

where $\mathbf{n}_j$ is the composite noise vector. Letting $\mathbf{G}$ denote the block diagonal matrix in (10), application of the transformations of (8) leads to:

$$\hat{\mathbf{y}}_j = \hat{\mathbf{G}} \hat{\mathbf{x}}_j + \hat{\mathbf{n}}_j = \hat{\mathbf{G}} \mathbf{L}_j \hat{\mathbf{u}}_j + \hat{\mathbf{n}}_j . \tag{11}$$

This equation represents the transfer equation of the $2Nr \times 2K$ effective channel. Note that except for the dimensions and the fact that it is real instead of complex, the effective channel is similar to the underlying MIMO channel (1). Therefore, all the definitions of the preceding section apply. In particular, it is easy to show that the instantaneous capacity for any $\mathbf{H}$ is

$$J_S(\mathbf{H}) = \frac{1}{2N} \mathrm{E}_{\mathcal{L}} \left[\log \det \left(\mathbf{I}_{2Nr} + \alpha \frac{S}{t} (\hat{\mathbf{G}} \mathbf{L} \mathbf{L}^T \hat{\mathbf{G}}^T) \right) \right], \tag{12}$$

where the expectation is taken over the ensemble from which $\mathbf{L}_j$ is chosen, and α is a normalizing constant which corrects for the scaling of signal power by $\mathbf{L}_j$. Outage probability, diversity order, outage capacity and capacity order can now be defined for the effective channel in exactly the same way as they were defined for the raw MIMO channel in the last section.

From the data processing theorem of information theory, the capacity of the space-time coded effective channel cannot exceed the capacity of the underlying MIMO channel. In fact, many space-time codes suffer a loss in outage capacity, as seen from the following theorem.

Theorem 3. The capacity order m_{eff} of a rate-R space-time code operating over a t-input, r-output Rayleigh channel satisfies

$$m_{\text{eff}} \le \min(t, r, R) . \tag{13}$$

Proof (sketch): Let v be the rank of a typical instance of the random matrix $\mathbf{M} = \hat{\mathbf{G}} \mathbf{L}$. Writing out the determinant in (12) in terms of the non-zero eigenvalues $\{\lambda_i\}$ of $\mathbf{M}$, we have

$$J_S(\mathbf{H}) = \frac{1}{2N} \sum_{i=1}^{v} \log\left(1 + \alpha \frac{S}{t} \lambda_i\right) = \frac{v}{2N} \log S + o(1/S).$$

Dividing by $\log S$ and letting $S \to \infty$ yields $m_{\text{eff}} = v/2N$. From the matrix dimensions, $\mathrm{rank}(\hat{\mathbf{G}}) \le \min(2Nt, 2Nr)$ and $\mathrm{rank}(\mathbf{L}) \le \min(2Nt, 2K)$. Since the rank of $\mathbf{M} = \hat{\mathbf{G}} \mathbf{L}$ cannot exceed the ranks of either $\hat{\mathbf{G}}$ or $\mathbf{L}$, we get

$$v = \mathrm{rank}(\mathbf{M}) \le \min(2Nt, 2Nr, 2K) . \tag{14}$$

Substituting $m_{\text{eff}} = v/2N$ into (14) finishes the proof. A more rigorous proof accounts for the randomness of $\mathbf{M}$ [8].

From the above theorem, a space-time code with rate $R < m = \min(t, r)$ decreases asymptotic outage capacity from approximately $m \log(S)$ to $R \log(S)$. Thus at high SNR, only a fraction R/m of the channel's outage capacity is achieved.

A low capacity order results in a shallow capacity asymptote. Similarly, a low diversity order results in a lower offset of the capacity asymptote, and hence a capacity loss that saturates at high SNR. However, it is very uncommon for space-time codes to have low diversity order. The raw diversity order, obtained using the rank criterion assuming independent inputs to the space-time code, is only a lower bound to the diversity order achievable by the use of well-designed outer codes. For example, consider the $K = t$, $N = 1$ serial-to-parallel converter which takes its t complex inputs over the t transmit antennas every signaling interval; it has a raw diversity order of r, since it provides no transmit diversity. But since the S/P converter does essentially no space-time coding, the effective channel is the same as the underlying MIMO channel itself, and the *achievable* diversity order of the effective channel is tr.

Since it is the achievable diversity order that directly affects capacity, the raw diversity order of a space-time has a much less dramatic impact on the outage capacity than does its rate.

We will close the section with an example of the effect of rate and diversity order on the outage capacity of space-time codes. We consider a Rayleigh fading channel with $t = 2$ transmit antennas, and either 1 or 2 receive antennas. We consider two rate-1 space-time codes: the Alamouti code of [10], and the repetition code, which takes in one complex symbol every signaling interval and transmits it from both antennas. The 1% outage capacity is plotted vs. SNR in Fig. 2.

Consider first the case of $r = 1$ receive antenna. In this case, both the Alamouti code and the repetition code have full capacity order; this follows because they both have rate 1, so that their effective capacity order is $m_{\text{eff}} = \min(2, 1, 1) = 1$, which matches the capacity order $m = \min(2, 1) = 1$ of the underlying 1×2 channel. This result is verified by Fig. 2, where the asymptotic slopes of the Alamouti and repetition capacity curves matches that of the underlying channel itself. In addition to full capacity order, the Alamouti code has full diversity order as well, so we expect it to lose very little capacity. Remarkably, as observed in the figure and proven in [5], the Alamouti code suffers no capacity penalty when there is only one receive antenna. The pathological repetition code, on the other hand, offers no transmit diversity even with an outer code, and its diversity order is just 1, a loss from the channel's diversity order of 2. The effect of the lower diversity order is the constant capacity loss at high SNR seen in Fig. 2.

When the receiver has two antennas, the diversity order increases to 4, and more importantly, the capacity order increases to 2. Meanwhile, Theorem 3 shows that the capacity order of both codes remain fixed at $\min(2, 2, 1) = 1$. Both codes can achieve at most 50% of the outage capacity of the underlying channel at high SNR. The capacity difference, in bits/s/Hz, grows without bound as SNR increases. As seen in Fig. 2, the outage capacity curve corresponding to the underlying channel has a slope that is twice as steep as those corresponding to the two space-time codes. Also notice that the repetition code, due to its lower diversity order (2 compared to 4), suffers an additional offset loss when compared to the Alamouti code.

IV. Weak Outer Codes: The Rate-Diversity Trade-Off

The outage capacity analysis so far implicitly assumes the presence of outer codes designed to achieve near-optimum performance. However, practical constraints on latency and complexity often prevent the use of strong outer codes. In this section, we examine the implications of the absence of outer codes on performance metrics for space-time codes. As mentioned in the previous section, the outage capacity depends directly on the achievable diversity order, and not the raw diversity order. When there is no outer code, the raw diversity order, by definition, determines the diversity gain and is clearly a crucial measure of performance. Since capacity is blind to so critical a parameter as the raw diversity order, the results obtained from a capacity-based analysis are not directly meaningful for stand-alone space-time codes.

The crucial determinants of performance of stand-alone codes are rate and raw diversity order. A high raw diversity order reduces error rates by protecting against deep fades. A high rate enables the use of a smaller constellation while still maintaining the same information rate, resulting in an increase of the minimum distance and lower susceptibility to additive noise. In other words, a higher raw diversity order increases diversity gain, and a higher rate increases the coding gain [2]. Ideally, one would like to have the best of both worlds by using space-time codes with high raw diversity order and high rate. (A high rate also leaves open the possibility of approaching capacity by using strong outer codes.) While it is theoretically possible to design codes with both these desirable properties, such codes have only been developed for a small range of channel dimensions [6]. Linear dispersion codes [4] are a promising high-rate option, but they do not necessarily have high raw diversity order, and also suffer from high decoding complexity when the channel dimensions are large.

Thus there is a trade-off between rate and raw diversity order. The question is: Given a target error probability and information rate, what combination of rate and raw diversity order minimizes the required SNR? In other words, is the reduction of coding gain caused by lowering rate compensated by the higher diversity gain obtained in the process? An exact answer to the above question depends on the dimensions of the channel and the class of space-time codes used. We provide a heuristic answer here.

Extrapolating Theorem 3 to the uncoded case, increasing the rate beyond $\min(t, r)$ does not buy any additional capacity order. So our first rule is that the rate need not be higher than $\min(t, r)$. The second heuristic rule is that beyond a total raw diversity order of 4, diminishing returns sets in and the additional diversity gain obtained by increasing the raw

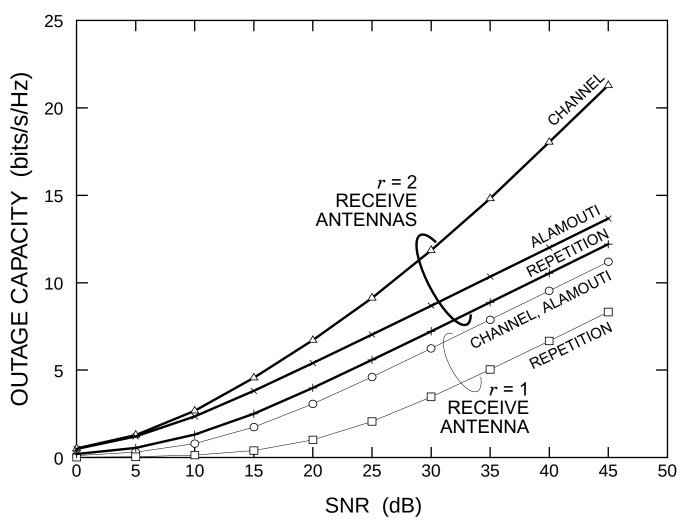

Fig. 2. Outage capacity versus SNR at 1% outage, assuming $t = 2$ transmit antennas.

diversity order is offset by the loss of coding gain due to the concomitant rate reduction. Combining the two rules, our design procedure is to start with a rate of $\min(t, r)$, and reduce the rate only so much as is necessary to obtain a raw diversity order equal to $\min(tr, 4)$, where the tr term accounts for channels whose full diversity order is less than 4.

With ML decoding at the receiver, the raw diversity order is guaranteed to be at least equal to the number of receive antennas. If the receiver has 4 or more antennas, the heuristic threshold on diversity order is met even without any transmit diversity. Therefore, according to our rule, one should use a space-time code with rate equal to $\min(t, r)$.

To support our heuristic rule, we present simulation results comparing two space-time codes operating over an 8×8 Rayleigh fading channel. The first encoder is a serial-to-parallel converter similar to the V-BLAST encoder [11], with a rate equal to the number of transmit antennas (8), and a raw diversity order equal to the number of receiver antennas (8). The GLST encoder, on the other hand, consists of a serial-to-parallel converter followed by four Alamouti [10] codes operating independently in parallel. (The 8 transmit antennas are divided into 4 two-antenna groups, with one Alamouti code for each group.) The total rate, equal to the sum of the rates of the four rate-1 Alamouti encoders, is equal to 4. The transmit diversity is 2, resulting in a total raw diversity order of $2r = 16$.

The GLST encoder is based on the generalized layered space-time architecture proposed in [1] as a method of achieving near-optimum performance on MIMO channels by using high diversity space-time codes. However, from the analysis in this paper, we know that the low rate GLST encoder incurs a heavy capacity penalty. In fact, even when there is no outer code, the number of receive antennas is large enough that the rate loss of the GLST encoder is more significant than the additional diversity gain obtained. So we expect the GLST encoder to perform worse than the VBT encoder.

Simulation results in Fig. 3 confirm this prediction. Independently fading blocks of 3200 uncoded bits are transmitted at an information rate of 32 bits per signaling interval, with 100 signaling intervals per block. To achieve the required information rate, the rate-8 VBT encoder uses 16-QAM, while the rate-4 GLST encoder uses 256-QAM. At the receiver, exact ML decoding was performed by the use of the sphere decoder [12].

With successive cancellation instead of ML decoding, the relative performance of the two decoders changes dramatically. With successive cancellation, the receive diversity order is only 1, and the raw diversity orders of VBT and GLST encoders are 1 and 2 (instead of 8 and 16 with ML decoding), respectively. Now, the rule of thumb would in fact have called for reducing the rate even further to obtain a diversity order of 4.

V. Conclusions

We studied the impact of the rate and diversity order of a space-time code on its performance. The outage capacity of a space-time code does not depend strongly on its raw diversity order, but a code with rate $R < \min(t, r)$ achieves at most a fraction $R / \min(t, r)$ of the outage capacity of the underlying channel at high SNR. Without an outer code, both high rate and high raw diversity order are desirable but difficult to find, implying a trade-off between rate and raw diversity order. We proposed a heuristic rule of thumb to strike a balance between rate and diversity order. In particular, when there are many receive antennas, we claimed that it is more important to use a high-rate code than a high-diversity-order code. Simulation results were shown to support this claim.

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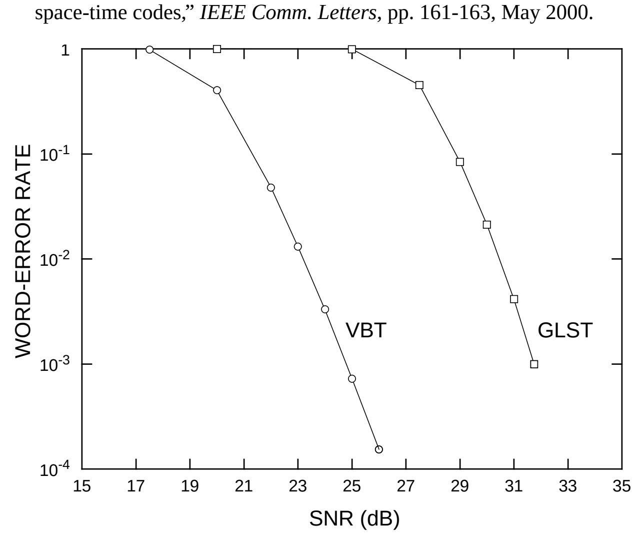

Fig. 3. Comparing the V-BLAST and GLST space-time codes.