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***Index Terms*—Layered space–time coding, multiple-input multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM), rate allocation, vertical Bell Labs layered space–time (V-BLAST).**

I. Introduction

EVER SINCE the revelation of the huge capacity of multiple-input multiple-output (MIMO) systems was shown by information theoretic analysis [1]–[3], great effort has been made by numerous researchers to design a practical system that approaches this attractive capacity.

One important MIMO technique is the vertical Bell Labs layered space–time (V-BLAST) structure proposed by Foschini [4], [5]. In the layered systems, the input data stream is demultiplexed, independently coded using 1-D coding, and sent via different transmit antennas simultaneously. The received signal from each substream is separated by nulling according to zero-forcing (ZF) or minimum mean-square error (MMSE) criterion and successive interference cancellation (SIC).

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The low complexity of layer processing makes the layered structure a very promising candidate for systems with a large number of transmit antennas and higher order modulation. However, in the original layered system, the input data is evenly divided into substreams and all layers have the same code rate. Due to the loss of signal energy and degree of freedom by nulling, the channel quality for the layers to be first detected is frequently poor, and cannot support reliable transmission with the given layer data rate. As a result, those layers that are detected earlier are more error-prone. To remedy this problem, optimum detection ordering has been proposed [6], [7]. The idea is to always select the layer with the best channel quality among the remaining layers to be detected first. A drawback of detection ordering is the high computational complexity, especially in frequency-selective channels. In systems such as wideband orthogonal frequency-division multiplexing (OFDM) systems, the channel responses are different for different subcarriers, making optimum detection ordering computationally intensive. Another issue is that the channel quality difference between different layers tends to decrease with increasing frequency selectivity, making the gain of using optimum detection order less pronounced. Therefore, the original V-BLAST system cannot achieve the full channel capacity, even with optimum detection ordering.

Rate adaptation and/or power allocation for layered structures depending on the instantaneous postprocessing signal-to-interference-plus-noise ratio (SINR) have been investigated in [8]–[10]. An interesting fact has been discovered that with MMSE interference nulling and a properly selected rate for each layer, the sum of capacities of all layers (with perfect SIC) is exactly the instantaneous open-loop capacity [11], [12]. To achieve the open-loop capacity, instantaneous rate feedback is needed, which introduces transmission overhead. In addition, for fast-varying environments, up-to-date rate feedback may not be feasible.

For channels with high frequency selectivity or enough time variation, the variations of layer capacities tend to decrease [13], as suggested by the law of large numbers. Thus, we can approach the open-loop channel capacity by determining the rate for each layer based on the knowledge of the channel statistics, but not of the actual realizations. In this paper, we propose a statistical rate-allocation approach for the layered space–time structure. The novel approach fixes the detection order, but allocates different data rates for different layers according to the detection order. Intuitively, the data rate should increase for later layers, since they have better channel quality compared with earlier detected layers. Our approach is to minimize the overall layer outage probability given the total information rate. The key difference of our work from that in [8]–[10] is that we capitalize on the statistical instead of instantaneous information of the channel, so that frequent rate feedback is not required. Furthermore, explicit feedback may not be necessary, since the required channel statistics are reciprocal in either a time-division duplex (TDD) or a frequency-division duplex (FDD) system [14].

The paper is organized as follows. The system model is briefly introduced in Section II, and the asymptotic optimum rate allocation is derived in Section III. Simulation results are given in Section IV, and the paper is concluded in Section V.

II. System Model

For a flat-fading MIMO system with N_t transmit and N_r receive antennas $(N_t \leq N_r)$, the relationship between transmitted and received signals can be expressed as

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n}$$

where $\mathbf{r}$ is a $N_r \times 1$ received signal vector, $\mathbf{s}$ is a $N_t \times 1$ transmitted signal vector, and $\mathbf{H}$ is an $N_r \times N_t$ channel matrix with entries being independent complex Gaussian random variables of zero mean and unit variance. The $N_r \times 1$ noise vector $\mathbf{n}$ has entries that are independent and identically distributed (i.i.d.) zero-mean circular complex Gaussian random variables with variance N_0. Assuming that each transmit antenna has the same transmit power, the instantaneous open-loop channel capacity is then [2]

$$C(\mathbf{H}, \rho) = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{\rho}{N_t} \mathbf{H}\mathbf{H}^H \right)$$

where $\mathbf{I}_{N_r}$ is an $N_r \times N_r$ identity matrix and ρ is the signal-to-noise ratio (SNR).

The layered structure was first proposed in [4] and [15]. The input data stream is evenly divided into N_t substreams that are independently encoded and sent via different antennas. The detection in layered systems is carried out sequentially. To detect the lth layer, interantenna interference from the detected layers is cancelled from the received signal by subtracting the reconstructed signals, i.e.,

$$\mathbf{r}_l = \mathbf{r} - \sum_{m<l} \mathbf{h}_m \hat{s}_m = \mathbf{r}_{l-1} - \mathbf{h}_{l-1} \hat{s}_{l-1}$$

where $\hat{s}_m$'s are the reconstructed signals of decoded layers. The lth column of $\mathbf{H}$ is denoted as $\mathbf{h}_l$. Then, linear nulling is used to suppress interference from all undetected layers, that is

$$z_l = \mathbf{w}_l^H \mathbf{r}_l$$

where the $N_r \times 1$ normalized weight vector $\mathbf{w}_j[n]$ nulls signals from all other undecoded layers according to the MMSE criterion. z_l is used as input to the decoder for the lth layer.

III. Rate Allocation for Layered Systems

In this section, we present our statistical rate-allocation approach for layered systems.

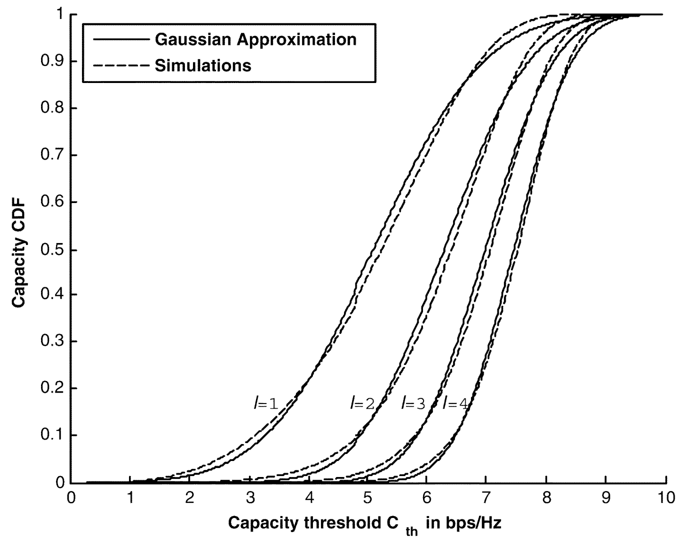


Fig. 1. Comparison of capacity CDF $\Pr(C \leq C_{\mathrm{th}})$ with Gaussian approximation and simulations, $N_t = 4$, SNR = 20 dB.

A. Statistical Rate Allocation

In the proposed approach, the detection order is fixed and the data rate for each layer is adjusted according to the channel quality and detection order of that layer. Without loss of generality, assume the order of detection is from transmit antenna 1 to N_t. The instantaneous information rate to be allocated to transmit antenna l is [11], [12], [16]

$$C_l = \log_2 \det \left(\mathbf{I}_{N_r} + \frac{\rho}{N_t} \mathbf{H}_{l-1} \mathbf{H}_{l-1}^H \right) - \log_2 \det \left(\mathbf{I}_{N_r} + \frac{\rho}{N_t} \mathbf{H}_l \mathbf{H}_l^H \right) \quad (1)$$

where $\mathbf{H}_l = [\mathbf{h}_{l+1}\, \mathbf{h}_{l+2} \cdots \mathbf{h}_{N_t}]$. It is obvious that $\mathbf{H}_0 = \mathbf{H}$.

It has been observed by various researchers that the distribution of the capacity of a MIMO channel, Rayleigh or Rician, can be accurately approximated by a Gaussian distribution at medium and high SNRs [17], [18]. Similarly, we try to approximate the distributions of instantaneous layer capacity by Gaussian distributions, denoted as

$$C_l \sim N\left(\eta_l, \sigma_l^2\right)$$

where η_l and σ_l^2 are the mean and variance of the capacity of the lth layer, respectively. Fig. 1 compares the capacity cumulative density function (CDF) obtained with Gaussian approximation and simulations, which demonstrates that the Gaussian approximation here is quite accurate. Table I gives the covariances of layer capacities in a 2×2 layered system obtained by simulating 10^6 independent channel realizations. From the table, the layer capacities are highly uncorrelated. Therefore, we assume that the layer capacities are independently distributed to facilitate our derivation.

When there are K independent channel realizations within each data transmission, the variance of layer capacity can be reduced and the the corresponding distribution is

$$C_{K,l} \sim N\left(\eta_l, \sigma_{K,l}^2\right)$$

where $\sigma_{K,l}^2 = (\sigma_l^2 / K)$.

TABLE I
COVARIANCES OF LAYER CAPACITIES IN A 2×2 LAYERED SYSTEM

SNR	σ_1^2	σ_2^2	cross covariance σ_{12}
14	2.0268	1.2138	-0.0942
16	2.2856	1.2533	-0.0780
18	2.5139	1.2868	-0.0626
20	2.7081	1.3031	-0.0443
22	2.8771	1.3170	-0.0352
24	2.9990	1.3261	-0.0229
26	3.1122	1.3297	-0.0208
28	3.1989	1.3343	-0.0118
30	3.2452	1.3391	-0.0112
32	3.3038	1.3398	-0.0063
34	3.3320	1.3451	-0.0049
36	3.3537	1.3447	-0.0048
38	3.3831	1.3439	0.0001
40	3.3820	1.3425	-0.0004

To obtain the optimum rate allocation, the mean and variance of layer capacities are needed. For a flat-fading i.i.d. complex Gaussian channel, the mean may be derived directly from the results by Telatar [2], which is an integral involving Laguerre polynomials, and no simple explicit expression is available. Simple approximate formulas by using asymptotic results in [19] and [20] may be used as an alternative. However, explicit expressions for a general channel model with spatial correlation are hard to derive, especially for the variance in frequency-selective channels. Therefore, we just compute the mean and variance by taking enough samples of the channel parameters, which is a feasible assumption, since the system can always get this information from past channel observations.

In order to obtain good statistics, a sufficient number of channel estimates should be taken within each coherence distance, where the channel statistics stay constant. The coherence distance of indoor channels is on the order of 5 m or less, while for macrocellular channels, up to 500 m have been measured. Given the speed of the terminal, we can easily determine the requirements for the frequency of taking channel measurements and updating the estimate of the channel statistics.

In order to properly select data rates for different layers, we minimize P_{out}, the outage probability of the whole layered system. It is equivalent to maximizing the probability when no layers have information rates greater than the respective layer capacities, i.e.,

$$1-P_{\text{out}}=\prod_{l=1}^{N_t}(1-P_l)=\prod_{l=1}^{N_t}\int_{u_l}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_{K,l}}e^{-\frac{(t-\eta_l)^2}{2\sigma_{K,l}^2}}\,dt$$

subject to the constraint that the total information rate is fixed

$$\sum_{l=1}^{N_t}u_l=C_T$$

where u_l is the information rate allocated to the lth layer. P_l is the outage probability for the lth layer.

Denote

$$u_l=x_l+\eta_l.$$

By setting up the equivalent Lagrangian, we try to find stationary points, i.e.,

$$J=\ln\left(\prod_{l=1}^{N_t}\int_{x_l}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_{K,l}}e^{-\frac{t^2}{2\sigma_{K,l}^2}}\,dt\right)-\lambda\left(\sum_{l=1}^{N_t}x_l+\sum_{l=1}^{N_t}\eta_l-C_T\right). \quad (2)$$

Direct calculation yields that the stationary point satisfies

$$-\frac{\frac{1}{\sqrt{2\pi}\sigma_{K,l}}e^{-\frac{x_l^2}{2\sigma_{K,l}^2}}}{\frac{1}{\sqrt{2\pi}\sigma_{K,l}}\int_{x_l}^{\infty}e^{-\frac{t^2}{2\sigma_{K,l}^2}}\,dt}=\lambda \quad (3)$$

for $l=1,2,\ldots,N_t$. Since we are only interested in the case when the input data rate is set such that reliable transmission is guaranteed most of the time, we assume that the outage probability given the total information rate is small, or equivalently, $x_l<0$, and $|x_l|\gg\sigma_{K,l}$, that is

$$\frac{1}{\sqrt{2\pi}\sigma_{K,l}}\int_{x_l}^{\infty}e^{-\frac{t^2}{2\sigma_{K,l}^2}}\,dt\approx 1.$$

Consequently, from (3)

$$-\frac{x_l^2}{2\sigma_{K,l}^2}\approx\ln\sigma_{K,l}+\frac{1}{2}\ln(2\pi\lambda^2). \quad (4)$$

By the constraint on total information rate

$$\sum_{l=1}^{N_t}\sqrt{-\left(\sigma_{K,l}^2\ln\sigma_{K,l}^2+\sigma_{K,l}^2\ln 2\pi\lambda^2\right)}=C_T-\sum_{m=1}^{N_t}\eta_m,\quad\text{or}$$
$$\sum_{l=1}^{N_t}\sqrt{-\left(\frac{\sigma_l^2}{K}\ln\frac{\sigma_l^2}{K}+\frac{\sigma_l^2}{K}\ln 2\pi\lambda^2\right)}=C_T-\sum_{m=1}^{N_t}\eta_m. \quad (5)$$

Since analytical solution to (5) is hard to obtain, we derive an asymptotic solution for the case with K independent channel realizations during each transmission and K going to infinity. Let $\lambda'=-\ln 2\pi\lambda^2$. Since the maximum of a number of values is greater than or equal to their average, it is easy to see that when K is large enough

$$-\frac{\sigma_{\max}^2}{K}\ln\frac{\sigma_{\max}^2}{K}+\frac{\sigma_{\max}^2}{K}\lambda'\geq\frac{1}{N_t^2}\left(C_T-\sum_{m=1}^{N_t}\eta_m\right)^2$$

where

$$\sigma_{\max}=\max\{\sigma_1,\sigma_2,\ldots,\sigma_{N_t}\}.$$

Then

$$\lambda'\geq\frac{K}{\sigma_{\max}^2}\left(\frac{1}{N_t^2}\left(C_T-\sum_{m=1}^{N_t}\eta_m\right)^2+\frac{\sigma_{\max}^2}{K}\ln\frac{\sigma_{\max}^2}{K}\right)$$

which implies that λ' asymptotically grows linearly with K. Therefore, we have

$$\sum_{l=1}^{N_t} \sqrt{\frac{\sigma_l^2}{K}\lambda'} \approx C_T - \sum_{m=1}^{N_t} \eta_m \tag{6}$$

since

$$\lim_{K\to\infty} \frac{\sigma_l^2}{K} \ln \frac{\sigma_l^2}{K} = 0$$

for $l = 1, 2, \ldots, N_t$. From (4), we have

$$x_l^* \approx \frac{\sigma_l}{\sum_{m=1}^{N_t} \sigma_m} \left(C_T - \sum_{m=1}^{N_t} \eta_m \right)$$

and the asymptotic optimum rate for the lth layer is

$$u_l^* \approx \eta_l + \frac{\sigma_l}{\sum_{m=1}^{N_t} \sigma_m} \left(C_T - \sum_{m=1}^{N_t} \eta_m \right). \tag{7}$$

Therefore, the asymptotic optimum outage probability for each layer is

$$\begin{aligned} P_l^* &= \int_{-\infty}^{x_l^*} \frac{1}{\sqrt{2\pi}\sigma_{K,l}} e^{-\frac{t^2}{2\sigma_{K,l}^2}} dt \\ &= \int_{-\infty}^{\frac{\sqrt{K}\left(C_T - \sum_{m=1}^{N_t} \eta_m\right)}{\sum_{m=1}^{N_t} \sigma_m}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt \end{aligned}$$

which is the same for all layers.

From (7), the asymptotic optimum data-rate allocation is that the data rate for each layer is backed off from the mean capacity of the layer, and the amount of backoff is proportional to the standard deviation of the layer capacity, which agrees with our intuition that more backoff is needed for layers with more variation in channel quality. In addition, the minimum overall layer outage probability is achieved when each layer has the same layer outage probability. Define the normalized capacity margin as

$$\varphi \triangleq \frac{\sqrt{K}\left(\sum_{m=1}^{N_t} \eta_m - C_T\right)}{\sum_{m=1}^{N_t} \sigma_m}.$$

The asymptotic optimum overall layer outage probability is then

$$\begin{aligned} P_{\text{out}}^* &= 1 - \prod_{l=1}^{N_t} (1 - P_l^*) \\ &= 1 - \left(\int_{-\varphi}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt \right)^{N_t} \end{aligned} \tag{8}$$

which states an interesting fact that the asymptotic minimum overall layer outage probability of a layered system is uniquely determined by the normalized capacity margin.

It should be noted that the approach proposed above can be applied to cases where the association of transmit antennas with substreams varies, or the channel is frequency-selective, such as OFDM systems. We only have to sum up all the data rates as given by (1) for each substream and determine the corresponding mean and variance of the channel capacity for each substream.

B. Relationship Between Outage Probabilities

In this subsection, we investigate some relationship between the outage probability of a layered system and that of the channel. Using the approximation [21]

$$\int_x^{\infty} e^{-\frac{t^2}{2}} dt \approx \frac{e^{-\frac{x^2}{2}}}{x} \ll 1, \quad x \gg 1 \tag{9}$$

Equation (8) can be simplified as

$$P_{\text{out}}^* \approx \frac{N_t}{\sqrt{2\pi}\varphi} e^{-\varphi^2/2}.$$

Similarly, we can obtain the asymptotic outage probability of the MIMO channel with the same overall information rate C_T as

$$P_{\text{ch}} \approx \frac{1}{\sqrt{2\pi}\varphi_{\text{ch}}} e^{-\varphi_{\text{ch}}^2/2}$$

where

$$\varphi_{\text{ch}} = \frac{\sqrt{K}\left(\eta_{\text{ch}} - C_T\right)}{\sigma_{\text{ch}}}$$

η_{ch} is the ergodic MIMO channel capacity, and σ_{ch}^2 is the variance of capacity of the flat-fading MIMO channel. Note that from (1)

$$\eta_{\text{ch}} = \sum_{l=1}^{N_t} \eta_l$$

and since

$$E\left\{ \left(\sum_l v_l \right)^2 \right\} \leq \left(\sum_l \sqrt{E\left\{v_l^2\right\}} \right)^2$$

for any set of random variables v_l's, we have

$$\sigma_{\text{ch}} \leq \sum_{l=1}^{N_t} \sigma_l.$$

Thus

$$\begin{aligned} \varphi_{\text{ch}} &= \frac{\sqrt{K}(\eta_{\text{ch}} - C_T)}{\sigma_{\text{ch}}} \\ &\geq \sqrt{K} \left(\sum_{l=1}^{N_t} \eta_l - C_T \right) \Big/ \sum_{l=1}^{N_t} \sigma_l = \varphi \\ \text{and} \quad P_{\text{out}} &\geq P_{\text{out}}^* \approx \frac{N_t}{\sqrt{2\pi}\varphi} e^{-\varphi^2/2} \\ &\geq N_t \frac{1}{\sqrt{2\pi}\varphi_{\text{ch}}} e^{-\varphi_{\text{ch}}^2/2} \approx N_t P_{\text{ch}} \end{aligned}$$

which implies that with the same overall information rate, the asymptotic outage probability of layered structures is at least N_t times that of the MIMO channel. However, the low complexity of a layered structure makes it still a good candidate for high-speed wireless systems.

IV. Simulation Results

In this section, we test the proposed statistical data-rate allocation by first analyzing its outage probability and comparing it with that of equal-rate V-BLAST and the channel outage probability. Then, a practical layered system is simulated to show the performance improvement in terms of word-error rate (WER) and effective throughput.

A. Comparison of Outage Probability

First, we use the outage probability to evaluate the performance gap between layered structure and the MIMO channel. We compare the outage probability of a 2×2 layered OFDM system with the channel outage probability, which may serve as a lower bound for WER of practical systems. Each substream is cyclically associated with transmit antennas at different subcarriers to effectively reduce the variation of layer capacities. The OFDM symbol structure conforms to the IEEE 802.11a PHY standard with 20 MHz system bandwidth in the 5 GHz band. We consider the performance in frequency-selective channels with correlated fading at the antenna elements. Specifically, the standard IEEE 802.11 TGn channel models "B" and "D" generated by the Matlab program available at [22] are used. Channel "B" has a shorter delay spread than channel "D," thus has less frequency selectivity.

Fig. 2(a) and (b) compare the outage probability of the proposed system and that of an unordered equal-rate V-BLAST system where the detection order is fixed. The total information rate per subcarrier is 9 b/s/Hz. It can be seen that for an outage probability of 1%, the gap between outage probability of the channel and that of the proposed system reduces from 3.2 dB for channel "B" to 1.3 dB for channel "D." It can be explained by the fact that increased frequency selectivity reduces the capacity variation of each layer. The SNR improvement for an outage probability of 1% is 6.3 and 3.6 dB for channels "B" and "D," respectively.

To test the sensitivity of the asymptotic optimum rate allocation to SNR, the outage probabilities of the rate allocation optimized for SNR = 24 dB are compared with those where the rates are optimized separately for each SNR. The performance degradation of optimized rate allocation for a fixed SNR is small in the 2×2 system, suggesting the robustness of the rate allocation to SNR disturbance. In addition, optimum rate allocation derived by a brute-force method is also demonstrated. In the brute-force method, each grid point with each coordinate being an integer multiple of 0.01 b/s/Hz is evaluated to find the optimum of (2). The approximate solutions and the solutions derived by brute-force method are further compared in Fig. 3(a) and (b) for channels "B" and "D," respectively. It can be seen that the approximate solution gives quite accurate results, while it is much simpler to obtain.

B. Performance Comparison in Practical Systems

Next, we compare the performance of practical 2×2 layered systems, given the same or similar total input information rate. Perfect channel estimation and synchronization is assumed. Each packet contains 1 kB of data and 10 000 packets are sent for each SNR. In the conventional system, each substream is coded using rate $3/4$ industry-standard convolutional coding, interleaved, and modulated using a 64 quadrature amplitude modulation (QAM) constellation. Two substreams are then sent simultaneously, resulting in a total data rate of 108 Mb/s. Each layer is fully deinterleaved and decoded before SIC.

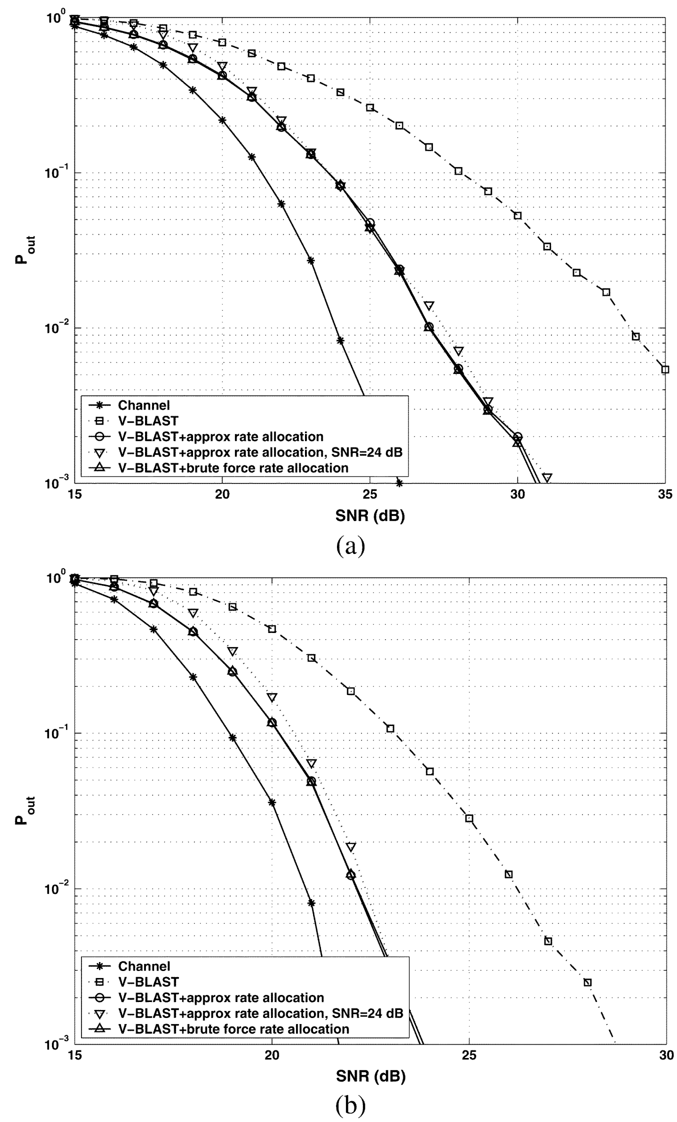
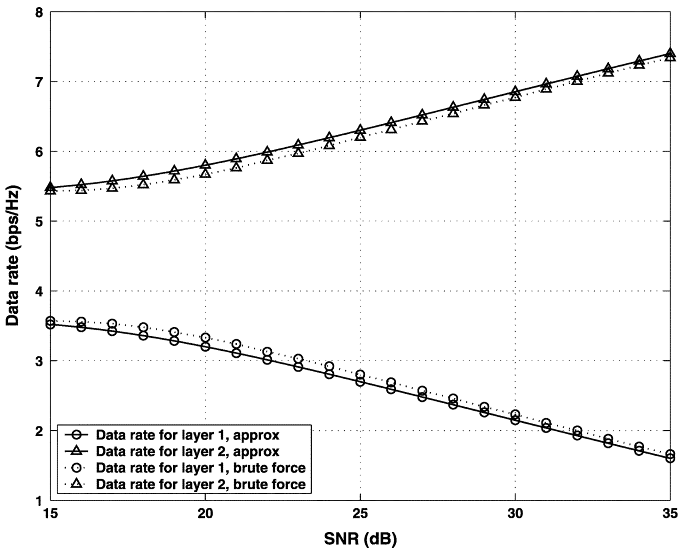
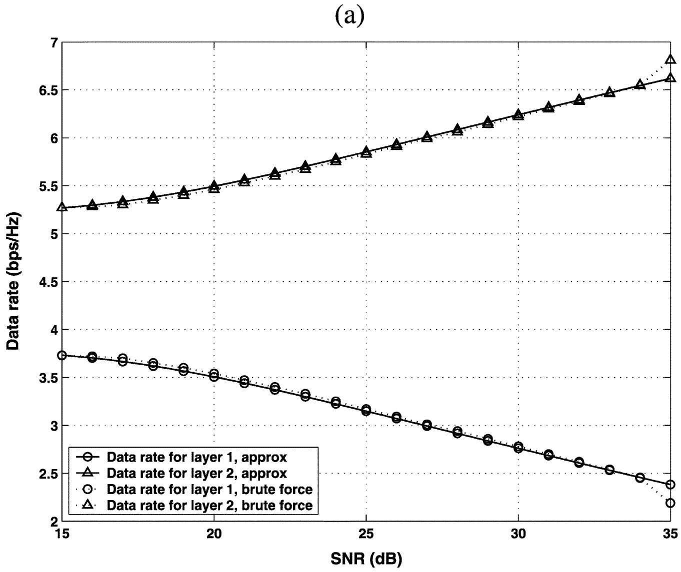


Fig. 2. Outage probability of statistical rate allocation for a 2×2 layered system. (a) Channel "B." (b) Channel "D."

Due to the limited number of supported data rates in a practical system, only binary phase-shift keying (BPSK), quaternaty (Q)PSK, 16 QAM, and 64 QAM with convolutional codes of rate $1/2, 2/3, 3/4$, and $7/8$ may be used for transmission of each layer. Therefore, the optimum data rates have to be quantized to the closest supported transmission modes and the code rates. Modulation schemes for different layers may be different depending on the statistics of layer channel quality after layered processing. The nominal total information rate as input to the rate-allocation algorithm is set such that the resultant total information rate after rate allocation is as close to that of the conventional system as possible to make the comparison reasonable. The rate allocation is optimized for the lowest SNR such that the optimum overall layer outage probability is below 1%. The optimized rates are then shown in Table II(a) and (b),

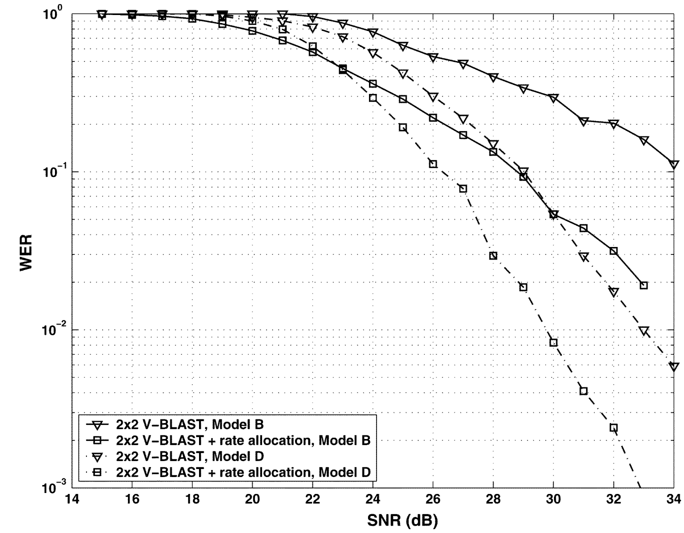


(a)

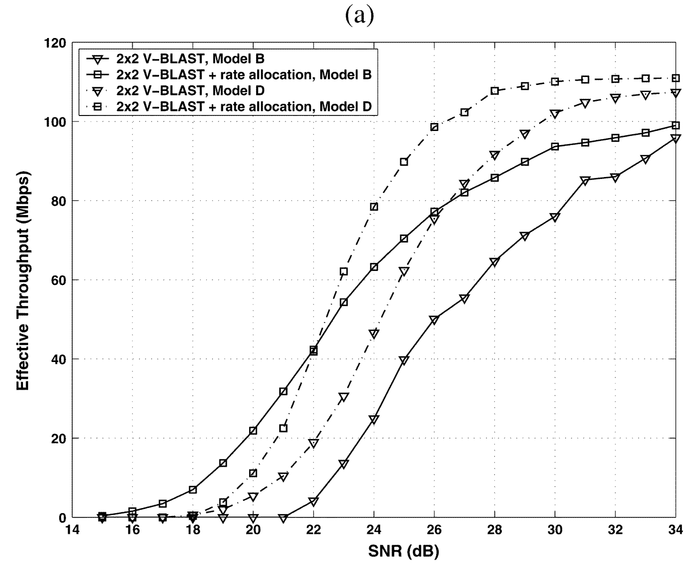


(b)

Fig. 3. Statistical rate allocation for a 2×2 layered system. (a) Channel "B." (b) Channel "D."



(a)



(b)

Fig. 4. Simulation results for a 2×2 layered system with statistical rate allocation, 1000 B packet, channels "B" and "D." (a) WER. (b) Effective throughput.

TABLE II
TRANSMISSION MODES OF DIFFERENT LAYERS IN A 2×2 SYSTEM WITH STATISTICAL RATE ALLOCATION. (A) CHANNEL "B." (B) CHANNEL "D."

Detection order	Modulation	Code rate	Layer data rate (Mbps)
1	16QAM	3/4	36
2	64QAM	7/8	63

(a)

Detection order	Modulation	Code rate	Layer data rate (Mbps)
1	64QAM	2/3	48
2	64QAM	7/8	63

(b)

for channels "B" and "D," respectively. The total data rate is 99 and 111 Mb/s, respectively, compared with the 108 Mb/s of the conventional layered system.

In Fig. 4(a), the WERs of the proposed system and the conventional layered system are shown. For a WER of 10%, the proposed system provides an SNR gain of about 5 and 3 dB for channel models "B" and "D," respectively. The effective throughput of the same system is shown in Fig. 4(b). From the figure, with the same SNR, the proposed system yields a maximum increase of about 38 and 32 Mb/s in effective throughput, for channels "B" and "D," respectively, while maintaining a similar peak data rate.

Finally, a 4×4 system is simulated and the results are shown in Fig. 5. For the equal-rate V-BLAST, each of the four substreams has the same configuration as the 2×2 case, with the total data rate being 216 Mb/s. The optimum rate allocations that deliver similar data rate are shown in Table III(a) and (b), with the resultant total data rates being 221 and 212 Mb/s, for channels "B" and "D," respectively. At a WER of 10%, the SNR gain of the proposed system is 4.5 and 6.7 dB for channel model "B" and "D," respectively, when compared with equal-rate V-BLAST. From Fig. 5(b), the maximum increase in effective throughput is about 91 and 174.5 Mb/s for channel "B" and "D," respectively.

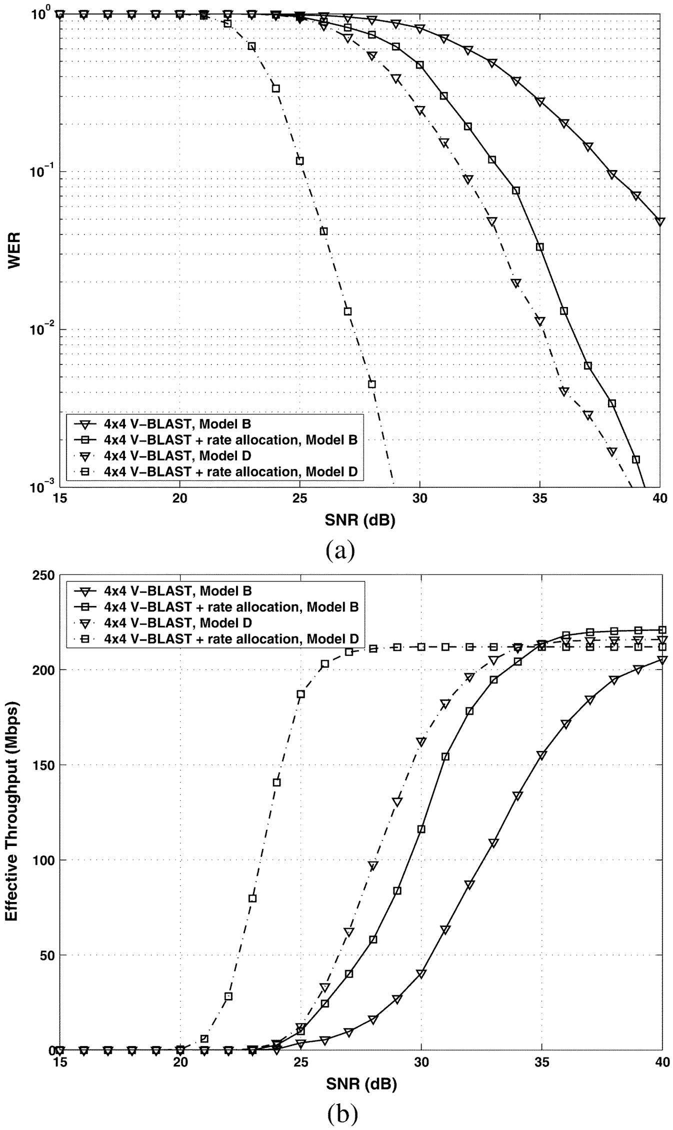


Fig. 5. Simulation results for a 4×4 layered system with statistical rate allocation, 1000 B packet, channels "B" and "D." (a) WER. (b) Effective throughput.

TABLE III
TRANSMISSION MODES OF DIFFERENT LAYERS IN A 4×4 SYSTEM WITH STATISTICAL RATE ALLOCATION. (A) CHANNEL "B." (B) CHANNEL "D."

Detection order	Modulation	Code rate	Layer data rate (Mbps)
1	16QAM	2/3	32
2	64QAM	7/8	63
3	64QAM	7/8	63
4	64QAM	7/8	63

(a)

Detection order	Modulation	Code rate	Layer data rate (Mbps)
1	16QAM	2/3	32
2	64QAM	3/4	54
3	64QAM	7/8	63
4	64QAM	7/8	63

(b)

V. CONCLUSION

In this paper, we propose a modified layered structure, where the detection order is fixed and the data rate for each layer is determined by the detection order and channel statistics. Using a Gaussian approximation of layer capacities, an asymptotic optimum data-rate-allocation algorithm is derived. Simulation results show significant performance improvement over the original V-BLAST structure. Furthermore, the system performance improves with increasing ergodicity within each codeword, making it promising for frequency-selective channels.

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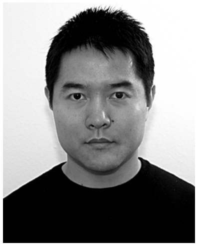

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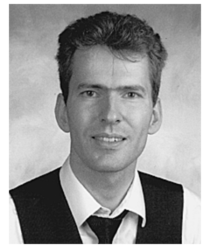

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