A Low Complexity Closed-loop BLAST Architecture

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Abstract- **Original form of BLAST can provide very high data rate but is susceptible to fading correlations between transmit antennas. In this paper, we proposed an improved form of BLAST architecture that employs a low rate feedback channel to adjust the transmission mode at the transmitter adaptively. An optimal criterion to select transmit antennas and modulation modes is derived based on zero-forcing technique. Simulation results in different scenarios show that the proposed closed-loop BLAST (or C-BLAST) outperforms the open-loop V-BLAST significantly, especially when the channel is ill-conditioned, since it judiciously selects a set of antennas to avoid disastrous fading correlations. Even in rich scattering environments, it still achieves some performance gain due to more efficient power allocations.**

I INTRODUCTION

With the anticipated increase in demand for higher data rate, especially in wireless downlink, there has been growing interest in spatial multiplexing scheme proposed as Bell-labs Layered Space-Time (BLAST) architectures [3,4]. Motivated by the theoretical research fact that the capacity can increase nearly linearly with the minimum number of transmit and receive antennas [1,2], BLAST can provide very high spectral efficiency with no additional power expenditure.

However, the scheme strongly relies on the richness of scattering environments, with the transfer functions between transmit and receive element pairs assumed mutually uncorrelated. While in real world scenario, they are usually not independent, but will exhibit certain fading correlations [5]. In a typical fixed wireless communication system, the base stations are located high above the clutter and thus it is unobstructed, in which case insufficient spacing will result correlation between base station antennas since the angle spread is relative small.

It is shown that fading correlation can lead to serious capacity degradation, assuming that the transmitter has no channel state information (CSI) [6,7,8]. Correspondingly, as an open-loop scheme, the performance of BLAST degrades significantly in the presence of fading correlations. However, with the channel information available at the transmitter, the capacity can be improved [9]. Even a small amount of feedback can increase the capacity appreciably, especially when channel is ill-conditioned (rank-deficient or fading correlated). Theoretically, when the channel is fully known at both the receiver and transmitter, water-filling maximizes the capacity [2]. However, to realize exact water-filling, the receiver must have the perfect CSI, which is undesirable since it needs a fast feedback and large amount of feedback data. Therefore many works concentrate on closed-loop systems with limited feedback. However, to date, most of works are solely focus either on capacity of information theory [9,10] or on some low spectral efficiency transmit schemes such as space-time block code [11,12].

In this paper, we will propose a low complexity BLAST architecture with a low rate feedback channel. Since it is operated in a closed-loop, we call it C-BLAST. With the CSI available at the receiver, C-BLAST judiciously selects fewer transmit antennas when the channel matrix is ill-conditioned. In order to keep the high spectral efficiency, some antennas in good condition may transmit with higher order modulation and more power to achieve higher data rate. In fact, it is a kind of capacity waste to apply lower order modulation to a good condition antenna. We will derive a criterion for selecting an optimum set of transmit antennas based on zero-forcing technique. Simulation shows that the scheme has remarkable performance improvement compared with original BLAST especially when the channel matrix is ill-conditioned.

The following section introduces our channel model and system structure. Optimal criterion is derived in Section III. Simulation results and discussion are followed in Section IV. Finally, in Section V contains our concluding remarks.

II CHANNEL MODEL AND SYSTEM STRUCTURE

In what follows, we will consider a single-user point-to-point communication channel with m transmit and n receive antennas. We assume the channel is flat fading and quasi-static. The channel is denoted as a matrix $\mathbf{H}^{n\times m}$, where h_{ij} is the complex channel gain from the j-th transmitter to the i-th receiver, for $j = 0, 1, \ldots, m-1$ and $i = 0$, 1, ..., n-1. The following discrete-time equivalent model is used

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \qquad (1)$$

where $\mathbf{x}$ is a $m \times 1$ vector whose the j-th component represents the signal transmitted from the j-th antenna. The received signal is a $n \times 1$ vector denoted by $\mathbf{y}$. $\mathbf{n}$ is a $n \times 1$ additive white complex gaussian noise vector with components drawn from i.i.d. wide-sense stationary processes with variance σ^2. The channel gain h_{ij} is modeled as complex gaussian random variable with variance 1. In the ideal rich scattering environment, these variables are independent. However, in practice, they will exhibit certain correlations. Define the correlation coefficient of i-th and j-th transmit antennas as

$$r_{ij} = \frac{E\{<\mathbf{h}_i, \mathbf{h}_j>\}}{\sqrt{E\{\|\mathbf{h}_i\|^2\} E\{\|\mathbf{h}_j\|^2\}}} \qquad (2)$$

Fig.1 shows the block diagram of our new closed-loop BLAST (C-BLAST) transmitter and receiver structure.

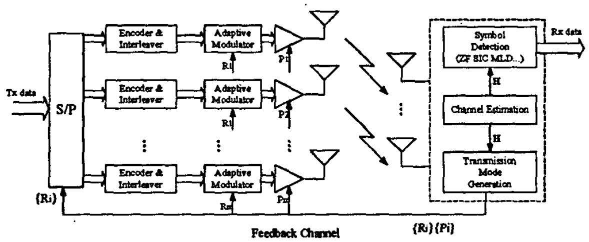


Fig.1 Block diagram of C-BLAST transmitter and receiver structure

Before we explain the system in details, some notations and definitions need to be introduced first. Let P_i denote the average power radiated by the i-th transmit antenna. The total transmission power $P_t = \sum_{i=1}^{m} P_i$ and transmit SNR (signal-to-noise rate) $\rho_t = P_t / \sigma^2$. Let R_i denote the spectral efficiency of the i-th transmit antenna, e.g. R_i=2 corresponds to QPSK modulation, R_i=3 corresponds to 8PSK modulation, R_i=4 corresponds to 16QAM modulation and etc. Particularly, R_i=0 means the i-th antenna is not used for transmission. Define the active antenna set as $\mathcal{A} \triangleq \{i \mid R_i > 0, \forall i\}$. Given total spectral efficiency R, define the *transmission mode* as a set $\{R_i\}$ such that $R = \sum_{i=1}^{m} R_i$.

The transmitter structure is very similar to V-BLAST while the main difference lies in the demultiplex process and the modulate process, which are adaptive to the feedback information drawn from the channel knowledge. The source data is first demultiplexed into several sub-streams by a serial to parallel converter adaptive to the spectral efficiency of each antenna. To be specific, the amount of data allocated to the i-th sub-stream is proportional to R_i. Then these sub-streams are coded and interleaved separately. After coding and interleaving, these data are modulated according to the transmission mode. We assume the same coding of each branch. So after modulation, these streams have the same symbol rate. Then the i-th sub-steam is transmitted by the i-th antenna with power controlled by P_i.

At the receiver, we assume that the channel $\mathbf{H}$ is perfectly estimated. The channel estimation is used for both symbol detection and transmission mode generation. The transmission mode and power allocation are fed back through a low rate feedback channel to adjust the transmitter. Our receiver model is quite general. It doesn't restrict the symbol detection method. Any kind of detection techniques proposed for original V-BLAST can be applied, such as maximum likelihood detection (MLD), zero-forcing (ZF) nulling, minimum mean-squared error (MMSE) nulling, or nulling in conjunction with cancellation including successive interference cancellation (SIC) and parallel interference cancellation (PIC). Furthermore, the strategy to decide transmission mode and power allocation may varies, which will strongly affected the overall performance of the system.

III OPTIMAL CRITERION

In our proposed system, the design of the criterion to decide transmission mode and power allocation is quite flexible. However we are most interested in the optimal criterion that finds the best transmission mode $\{R_i\}$ and corresponding power allocation $\{P_i\}$ given the channel $\mathbf{H}$, the spectral efficiency constraint R and the power constraint P_t. The definition of "best" may varies by the specific applications. Here we can define it as to minimize the average bit err rate (BER). However, the BER performance of the system is related to the symbol detection approach adopted by the receiver. Therefore, under different detection methods, different optimal criterions may be derived. In what follows, we will derive an optimal criterion based on zero-forcing technique, which is the simplest among all detection approaches. By this technique, each sub-stream is in turn considered to be the desired signal, and the remainders are considered as "interferers". Nulling is performed by simply multiplying a matrix inversion called decorrelating filter. The decorrelating filter $\mathbf{G}^{m\times n}$ is defined as the pseudo-inverse of **H**

$$\mathbf{G} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H \tag{3}$$

And the output vector of the decorrelating filter can be written as

$$\hat{\mathbf{x}} = \mathbf{G}\mathbf{y} = [(\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H](\mathbf{H}\mathbf{x}+\mathbf{n}) = \mathbf{x} + \mathbf{G}\mathbf{n} \tag{4}$$

Thus we can detect each component signal separately. However, it enhances the noise contribution relative to signal. To evaluate this, let $\mathbf{G} = (\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_n)^T$, where $\mathbf{w}_i$ denotes the i-th row of **G**, it follows

$$\hat{x}_i = x_i + \mathbf{w}_i\mathbf{n} \quad \text{for i} = 0, 1, \ldots, m\text{-}1 \tag{5}$$

Then the average SNR of the i-th sub-stream after decorrelating detection can be written as

$$\tilde{\rho}_i = \frac{P_i}{\sigma^2\|\mathbf{w}_i\|^2} = \rho_i / \|\mathbf{w}_i\|^2 \tag{6}$$

As shown in (6), we note that the average received SNR is just the transmit SNR divided by a factor $\|\mathbf{w}_i\|^2$. We will briefly discuss how fading correlation affects this value. Let $\mathbf{H} = (\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_n)$ where $\mathbf{h}_i$ is the channel vector corresponds to the i-th transmit antenna. Given a specific realization of **H**, we can write the instantaneous correlation coefficient of i-th and j-th transmit antennas as

$$r_{ij} = \frac{<\mathbf{h}_i, \mathbf{h}_j>}{\|\mathbf{h}_i\|\|\mathbf{h}_j\|} \tag{7}$$

According to the definition of $\mathbf{w}_i$ we have

$<\mathbf{w}_i, \mathbf{h}_i> = 1$ and $<\mathbf{w}_i, \mathbf{h}_j> = 0 \quad i \neq j$

By some basic linear algebra, we derived the following lower-bound of $\|\mathbf{w}_i\|^2$

$$\|\mathbf{w}_i\|^2 \geq \frac{1}{\|\mathbf{h}_i\|^2 \sqrt{1 - \max_{j,j\neq i} |r_{ij}|^2}} \tag{8}$$

From (8), we observe that $\|\mathbf{w}_i\|^2$ is related to both $\|\mathbf{h}_i\|$ and $|r_{ij}|$, either a decrease of $\|\mathbf{h}_i\|$ because of channel fading of i-th transmit antenna or an increase of $|r_{ij}|$ because of the correlation with other antennas will result the enlargement of $\|\mathbf{w}_i\|^2$. Particularly, $\|\mathbf{w}_i\|^2$ will converge to infinite as $|r_{ij}|$ converges to 1. Therefore $\|\mathbf{w}_i\|^2$ in some sense represents the channel condition of the i-th transmit antenna. A strong fading correlation will result in an abnormally large $\|\mathbf{w}_i\|^2$, which will deteriorate the receive SNR of i-th sub-stream significantly thus degrading the overall performance.

Suppose R is the total spectral efficiency we want to keep. Our problem is equivalent to minimize the average transmission power P_t while keeping the total average BER under a specific value, e.g. 10^{-3}. Assume the received signal to noise rate per bit is at least ρ_{R_i} to ensure the given BER value as the spectral efficiency is R_i. Then the total transmission power will be

$$\sigma^2 \sum_{i=1}^{n} \left(\|\mathbf{w}_i\|^2 R_i \rho_{R_i} \right) \tag{9}$$

When we adopt an active antenna set $\mathcal{A}$ for transmission. The channel vector corresponds to the unused antenna is set to zero, i.e. $\mathbf{H}^{\mathcal{A}} = (\mathbf{h}_1^{\mathcal{A}}, \mathbf{h}_2^{\mathcal{A}}, \ldots, \mathbf{h}_n^{\mathcal{A}})$ and $\mathbf{h}_i^{\mathcal{A}} = 0$ *if* $i \notin \mathcal{A}$. Note that the value of $\|\mathbf{w}_i\|^2$ is the function of $\mathcal{A}$, denoted as $\|\mathbf{w}_i^{\mathcal{A}}\|^2$. The reduction of non-zero channel vector will result the melioration of $\|\mathbf{w}_i\|^2$. Now the total transmission power becomes

$$\sigma^2 \sum_{i\in\mathcal{A}} \left(\|\mathbf{w}_i^{\mathcal{A}}\|^2 R_i \rho_{R_i} \right) \tag{10}$$

We want to minimize this value. Note here σ^2 is a constant. And we may use normalized value of ρ_{R_i} instead of real value. For instance, we may let $\rho_2 = 1$ and at high SNR we approximate $\rho_3 = 2.27$, $\rho_4 = 2.5$ and etc.

Therefore, we arrive at our final optimal criterion

$$\widehat{\mathcal{A}}, \{\widehat{R}_i\} = \arg\min_{\mathcal{A}, \{R_i\}} \sum_{i\in\mathcal{A}} \left(\|\mathbf{w}_i^{\mathcal{A}}\|^2 R_i \rho_{R_i} \right) \tag{11}$$

with the constraint: $\sum_{i=1}^{m} R_i = R$

And the corresponding power allocation $\{P_i\}$

$$P_i = P_t \frac{\|\mathbf{w}_i^{\mathcal{A}}\|^2 R_i \rho_{R_i}}{\sum_{k\in\mathcal{A}} \left(\|\mathbf{w}_k^{\mathcal{A}}\|^2 R_k \rho_{R_k} \right)} \quad \text{for } i \in \mathcal{A} \tag{12}$$

We must point out that our derivation is based on the zero-forcing detection method. It is easy to see that it is optimal when using zero-forcing and it doesn't ensure its optimum under other detection methods. However, we may derive optimal criterions based on those detection methods in a similar way. For instance, we can replace the decorrelating matrix with MMSE nulling matrix to derive the optimal criterion based on MMSE nulling.

IV Numerical Results and Discussions

In this section, we will implement the criterion to the closed-loop system introduced at the beginning to provide some numerical results. In all simulations, we consider an uncoded system with four transmit antennas. We suppose the total spectral efficiency R is constrained to 8 bit/s/Hz. And at each transmit antenna, only two modulation modes are adopted: QPSK and 16QAM which correspond to R_i=2 and R_i=4 respectively. We let $\rho_2 = 1$ arbitrarily, and the corresponding normalized SNR factor $\rho_4 = 2.5$, which is derived at high SNR.

Fig.2 shows the performance comparison between C-BLAST and V-BLAST with 4 transmit and 6 receive antennas. In both schemes, ZF detection is adopted at the receiver. As we may see, C-BLAST outperforms V-BLAST significantly. Even when all transmit antennas are mutually uncorrelated (r=0), C-BLAST still has 4 dB gain over V-BLAST at BER=10-3. With the increase of correlation between two of the transmit antennas, the performance of V-BLAST degrades quickly and saturates at an unacceptable level, while C-BLAST scheme still maintains fairly good performance, with only less than 1 dB degradation as r=0.9.

We may refer to Fig.3 to analyze how we achieve this performance gain. Fig.3 shows the probability statistics of number of transmit antennas used for transmission under different degrees of transmit antenna correlations. When the antennas are all uncorrelated. C-BLAST tends to choose all antennas with the same modulation in most situations as V-BLAST does. The relative less performance gain is achieved mainly due to the more efficient power allocation of each antenna. When the correlation coefficient increases, the probability of using four antennas decreases while that of using three antennas increases. At the extremity of r=0.99, C-BLAST only chooses the better one of two strongly correlated antennas and the other one is always dropped. However, V-BLAST use both antennas for transmission and the data stream of these two antennas can hardly be separated by the receiver.

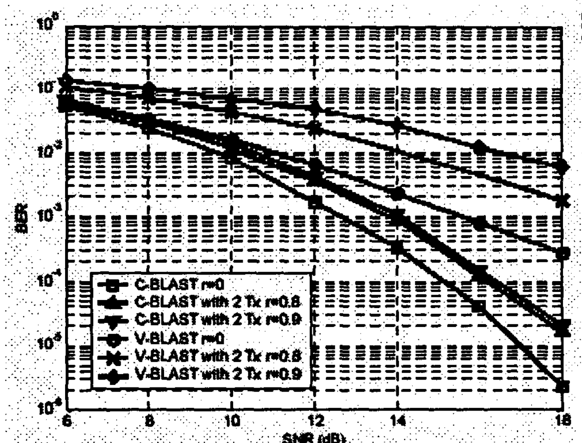
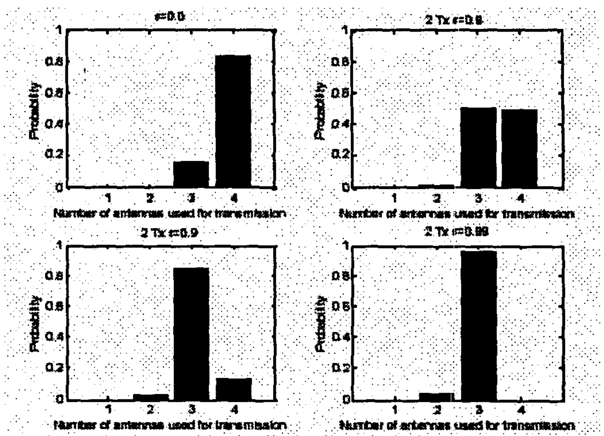


Fig.2 Performance comparison with different Tx correlations, (m, n)=(4, 6), ZF detection

Fig.4 shows the performance comparison between C-BLAST and V-BLAST with 4 transmit and 4 receive antennas. We find that even r=0, pure ZF detection behaves quite poor in V-BLAST while C-BLAST maintains acceptable performance. Detail simulation shows that in this scenario, C-BLAST scheme tends to choose 2 or 3 antennas instead 4 antennas in most situations since the number of receive antennas is just equal to that of transmit antennas.



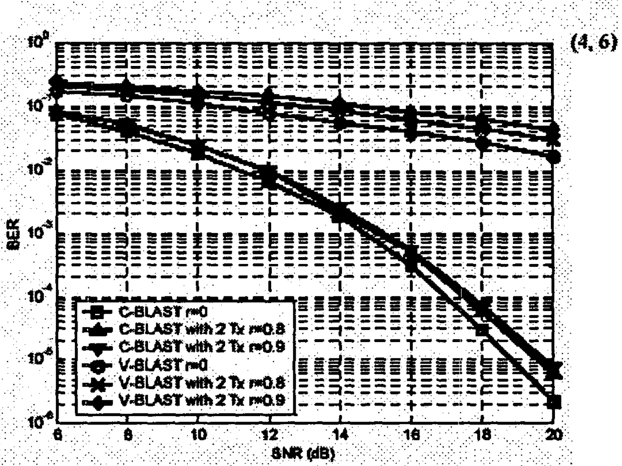


Fig.4 Performance comparison with different Tx correlations, (m, n)=(4, 4), ZF detection

As we have mentioned above, our optimal criterion doesn't ensure its optimum under other detection methods other than ZF. However we may expect some performance improvement since it generally meliorates the space distribution of joint constellations, and enlarges the minimum distance of the signals. Detail simulations shows that under other detection methods such as ZF-SIC ZF-PIC and MLD, C-BLAST still outperforms V-BLAST although with less performance gain. Fig.5 shows the performance comparison between C-BLAST and V-BLAST under the optimum detection method with high complexity known as maximum likelihood detection (MLD).

Compared with Fig.4, we find that in C-BLAST architecture, the BER performance of ZF detection is nearly as good as that of MLD detection. This contrasts sharply with the common belief that ZF detection usually gives poor performance. In our proposed closed-loop system, even simple ZF detection can achieve quite acceptable result. However, this extraordinary performance depends on precise power allocation, which requires relative large amount of feedback data. Certain quantification will significantly reduce the amount of feedback while resulting some performance penalty at the same time. A reasonable tradeoff between feedback amount and performance needs to be investigated in practical systems.

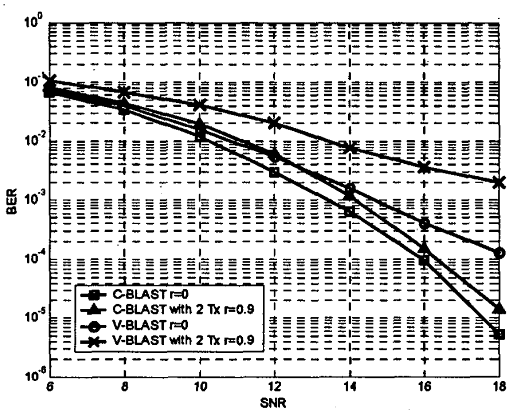


Fig.5 Performance comparison with different Tx correlations,

(m, n)=(4, 4), MLD detection

V CONCLUSIONS

In this paper, we have proposed a closed-loop BLAST (C-BLAST) architecture. According to the channel status, it judiciously adjusts the transmission mode at the transmitter to avoid disastrous fading correlations. An optimal criterion based on zero-forcing technique was derived. Simulation results showed that our proposed C-BLAST outperformed V-BLAST, especially in presence of fading correlations between transmit antennas. Since our system is based on simple antenna selection, modulation adaptation and power control, it only needs a low rate feedback channel. Thus low complexity and high robustness can be expected. Some practical issues for implementation will be investigated in future research.

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