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Adaptive Spatial Multiplexing Techniques for Distributed MIMO Systems

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Abstract— **In this paper, adaptive spatial multiplexing techniques for distributed MIMO (D-MIMO) systems are proposed, where the mobile co-located with multiple antennas is capable of receiving distinct sub-streams from multiple widely separated antennas. In order to take advantage of the macrodiversity gain in D-MIMO, we propose link adaptation methods exploiting macroscopic channel information. We compare the performances of different link adaptation methods for the conventional co-located MIMO (C-MIMO) systems and D-MIMO systems. Simulation results reveal that for D-MIMO, link adaptation only based on the knowledge of large-scale fading (a lower bound for the performance of link adaptation in D-MIMO) performs even better than the link adaptation based on singular value decomposition for C-MIMO (an upper bound for the performance of link adaptation in C-MIMO) in a large range of interest. Thus in D-MIMO, macrodiversity protection not only provides capacity gain in information theoretic aspect, but also can be effectively exploited in the real signal processing scenario. This link adaptation scheme can be done on the order of the coherence time of the large-scale fading, offering an excellent tradeoff between performance and complexity. Finally, we notice that more detailed channel knowledge at the transmitter and receiver side of both D-MIMO and C-MIMO can be traded for even higher performance gain, which may be feasible in some slow-varying environments.**

Index Terms— **Link adaptation, Macrodiversity, MIMO systems.**

I. INTRODUCTION

As the demand for high quality and capacity grows for wireless communication systems, distributed antenna systems (DAS) draw considerable attention recently, which can counteract large-scale fading, improve coverage, link quality and system capacity because of its inherent macroscopic diversity and average shortened access distance [1][4].

As a generalization of the distributed antenna systems, distributed MIMO systems (D-MIMO) are formally proposed in [6], which can address many problems inherent in conventional co-located MIMO (C-MIMO) systems. As depicted in Fig. 1, the key difference between D-MIMO and C-MIMO is that multiple antennas for one end of communications are distributed among multiple widely separated radio ports, and independent large-scale fading is experienced for each link between a mobile-port pair. Also, we can reasonably assume that the multiple ports in D-MIMO are connected by a high-speed backbone that allows information to be reliably exchanged among them, such that joint and co-operative processing is possible. Our discussion can also be extended to the case where antenna elements at both ends are widely separated in geography, like in sensor networks.

In order to realize very high spectral efficiency, spatial multiplexing schemes such as Bell-labs layered space-time architecture (BLAST) are widely used in MIMO communications. Open-loop V-BLAST that does not need instantaneous channel information feedback at the transmitter was proposed in [5], which simply allocates equal power and rate to every transmit antenna. Consequently, antenna experiencing the deepest fading limits the performance. Per-antenna link adaptation for an extension of V-BLAST based on perfect channel state information (CSI) has been proposed for C-MIMO systems recently to address this problem [2]. However, the tracking and feedback of the instantaneous channel information incur large system overhead and/or high computational complexity.

In D-MIMO, large-scale fading seen by each distributed port is independent, therefore the CSI is a combination of both large-scale fading and small-scale fading. Thus in D-MIMO, macrodiversity provides another degree of freedom for link adaptation, which doesn't exist for C-MIMO. Motivated by these observations, we propose several adaptive spatial multiplexing schemes for D-MIMO exhibiting different tradeoff between performance and complexity, all of which assume advantages over their C-MIMO counterparts due to macrodiversity gain inherent in D-MIMO.

The paper is organized as follows. The D-MIMO model is described in Section II together with its macrodiversity gain in terms of channel capacity. Then the link adaptation methods for both C-MIMO and D-MIMO spatial multiplexing systems are discussed in Section III. Simulation results are shown and analyzed in section IV. Finally, conclusions are presented in section V.

II. D-MIMO SYSTEM MODEL AND MACRODIVERSITY PROTECTION

We consider a mobile equipped with M co-located receive antennas, around which are K radio ports with N antennas per port. We refer to such a system as an (M,N,K) distributed MIMO system as shown in Fig.1. Note that the conventional C-MIMO in a standard cell can be regarded as an $(M,N,1)$ distributed MIMO system. We also assume that these distributed ports are connected to a central processor where all complex signal processing is done.

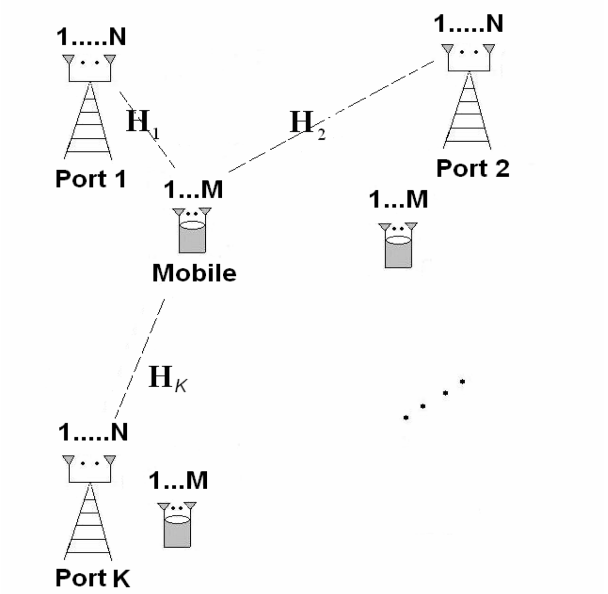

Fig.1. Proposed (M,N,K) distributed MIMO systems with M antennas at each mobile station and N antennas at each of the K radio ports.

Assume the channel is flat fading and quasi-static. Without loss of generality, we consider an $(M,1,K)$ D-MIMO system, which can be described as

$$\mathbf{r} = \mathbf{H}_s\mathbf{F}\mathbf{x} + \mathbf{n}\,, \tag{1}$$

where $\mathbf{x}$ and $\mathbf{r}$ are the transmitting and receiving vectors respectively, and $\mathbf{n}$ is the complex additive white Gaussian noise vector with co-variance matrix $E(\mathbf{n}\mathbf{n}^H) = \sigma^2\mathbf{I}$. The small scale fading is modeled as Raleigh, represented by an $M \times K$ matrix $\mathbf{H}_s$ with i.i.d normalized Gaussian $\mathfrak{N}(0,1)$ entries. The large-scale fading is represented by a locally stationary $K \times K$ diagonal matrix $\mathbf{F} = diag(\alpha_1, \alpha_2, ..., \alpha_K)$. Both shadowing and path loss effects are incorporated in the diagonal entries of $\mathbf{F}$ with $\alpha_k^2 = Cs_k / d_k^r$, where the shadowing is represented by an independent log-normal random variable s_k, and d_k is the access distance between the subscriber and the $k-th$ nearest distributed antenna with the path loss exponent r. The generalized paradigm for an (M,N,K) D-MIMO can be found in [6].

One of the advantages of D-MIMO over C-MIMO is the power gain achieved by macrodiversity, as seen from the horizontal gap between the parallel capacity curves of (4,1,4) D-MIMO and (4,4,1) C-MIMO in Fig. 2. Intuitively, the variance of the instantaneous channel capacity due to large-scale fading is greatly reduced in D-MIMO and thus less outage is seen. Macrodiversity protection in D-MIMO can be effectively exploited to adapt the data transmission for better system performance, as illustrated in the following section.

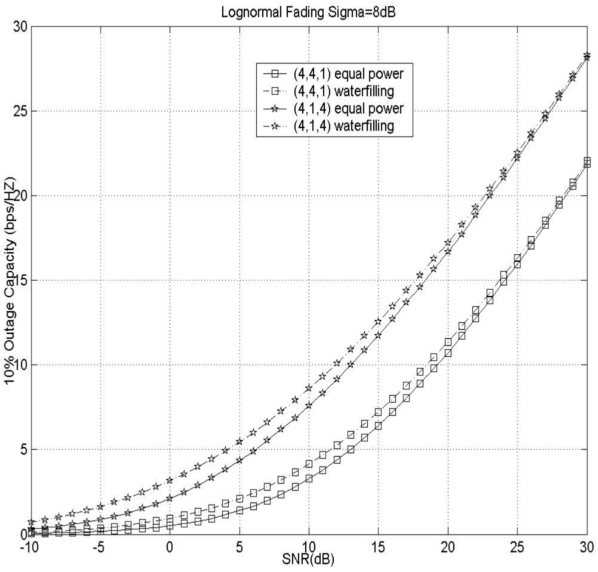

Fig.2. 10% outage capacity of D-MIMO and C-MIMO.

III. LINK ADAPTATION FOR C-MIMO AND D-MIMIO V-BLAST

Link adaptation techniques refer to adjusting the modulation constellation size, power level, and/or other signal transmission parameters such as coding rate, spreading factor, signaling bandwidth, and signaling scheme according to the changing environments, so as to take advantage of prevailing channel conditions. For simplicity, we only consider uncoded modulation, and the adaptive transmission parameters are the data rate and power level of each link. Implicitly, the number of simultaneously transmitted data streams (and thus actively utilized antennas and radio ports) is also adapted according to the channel conditions.

Data throughput, bit error rate (BER) and power consumption are three important and often competing optimization objectives in the design of a wireless network. In our study, it is assumed that the channel gains of the decomposed K substreams in MIMO are given, on which we want to determine a bit allocation scheme $\{b_k\}$ such that $\sum_{k=1}^{K} b_k = B$ and a power allocation scheme $\{P_k\}$ such that $\sum_{k=1}^{K} P_k = P$, so as to achieve the minimum error rate. In practice, the bit rate assignments are often constrained to be multiples of some base unit (e.g. multiples of 2 for square QAM modulation). We can show that this joint optimization problem can be effectively decomposed into two steps.

Step1. Total transmit bits are allocated over subchannels so that the total transmit power is minimized for the same target BER. The basic idea is to put each unit of bits to the subchannel with the least required energy. Initially bits will be assigned to the best subchannel (with the largest channel gain), but later on there is a tradeoff in putting additional bits to loaded good subchannels and unloaded not-so-good subchannels, as the required energy to transmit one more bit increases as the modulation constellation size increases. Mathematically, the bit loading is done recursively as follow.

```
$b_k = 0, \quad 1 \le k \le K$
while  $B > 0,$
{
$k^* = \arg\min_k [(P(b_k + \Delta b) - P(b_k)) / \Phi_k^2];$      (2)
$b_{k^*} = b_{k^*} + \Delta b;$
$B = B - \Delta b;$
}
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where $P(b_k)$ is the required energy to transmit b_k bits for a target BER with some type of modulation, Δb is the bit allocation base unit, and Φ_k is the gain for the $k-th$ subchannel. In practice, this bit loading can be implemented with efficient algorithms such as discrete margin-maximization algorithm in [3].

Step2. After bit allocation, the total transmit power is allocated among the links in such a way that each link achieves the same minimum Euclidean distance in the modulation constellation and thus the same BER. Intuitively, the system performance is limited by the worst subchannel. Therefore, the aggregate performance is approximately maximized if the BERs in all used subchannels are equal.

Link adaptation is anticipated to significantly improve the performance of MIMO systems. Meanwhile, link adaptation requires certain CSI at the transmitter which incurs extra system overhead and complexity. In the following, several adaptive spatial multiplexing schemes for C-MIMO and D-MIMO are illustrated, the performances of which will be compared in Section IV.

A. Link adaptation for C-MIMO and D-MIMO based on SVD

Singular value decomposition (SVD) based link adaptation method can be used as an performance upper bound. For a MIMO channel ($\mathbf{H}_s$ for C-MIMO and $\mathbf{H}_s\mathbf{F}$ for D-MIMO) with SVD $\mathbf{U\Sigma}V^*$, if the transmitter filter is $\mathbf{V}$ and receive filter is $\mathbf{U}^*$, then the diagonal elements in $\mathbf{\Sigma}$ can be viewed as the gains for each decomposed subchannel. In (2), let $\Phi_i = \mathbf{\Sigma}(i,i)$, then we can implement bit loading and power allocation for these decomposed subchannels.

B. Link adaptation for C-MIMO and D-MIMO based on post- detection SNR

In what follows, we will explain how the link adaptation algorithm described above can be applied when the receiver employs V-BLAST technique. We know that V-BLAST is in fact a cancellation and nulling algorithm [5]. Assume no error propagation during the detection procedure, then V-BLAST algorithm decomposes the $M \times N$ C-MIMO channel into N subchannels, which can be described as

$$y_{k_i} = \mathbf{w}_{k_i}^H * \mathbf{r}_{k_i} = x_{k_i} + \mathbf{w}_{k_i}^H * \mathbf{n}\,.\ i = 1,2,3,...,N\ , \tag{3}$$

where $\mathbf{r}_{k_i}$ is the detection vector for the k_i-th substream resulting from subtracting the detected data substreams from the receiving vector, and $\mathbf{w}_{k_i}^H$ is the nulling vector to cancel the interference from the non-detected substreams. The post-detection SNR for the k_i-th detected component of $\mathbf{x}$ is $\gamma_{k_i} = \dfrac{<|x_{k_i}|^2>}{\sigma^2 \|\mathbf{w}_{k_i}\|^2}$, therefore equivalently, we can consider $\dfrac{1}{\|w_{k_i}\|}$ as the gain for the k_i-th decomposed subchannel. In (2), we can let $\Phi_{k_i} = \dfrac{1}{\|w_{k_i}\|}$, then we can obtain the bit loading and power allocation for each decomposed subchannel.

Similarly, for the D-MIMO channel, the post detection SNR for the i-th subchannel is

$$\gamma_i = \frac{|< x_i >|^2 \alpha_i^2}{\sigma^2 \|w_i\|^2}\quad , \tag{4}$$

and the gain of the i-th decomposed subchannel can be viewed as $\Phi_i = \dfrac{\alpha_i}{\|w_i\|}$.

C. Link adaptation for D-MIMO only based on large scale fading

Following discussions in III.B, usually α_i “dominates” the gain of the i-th decomposed subchannel of D-MIMO, then we can implement bit loading and power allocation only based on large scale fading for D-MIMO, i.e., $\Phi_i = \alpha_i$.

The advantage of this link adaptation strategy is that the large scale fading, which is locally stationary and varies at a much slower rate, makes itself much easier measured and updated. So this method offers an excellent tradeoff between complexity and performance. We can also view this method as a lower bound for the performance of link adaptation in D-MIMO, since it only uses partial channel information.

IV. SIMULATION RESULTS

To illustrate the effectiveness of our proposed link adaptation methods, the BER performances of the above signaling schemes are compared for a (4,4,1) C-MIMO and a (4,1,4) D-MIMO with 8 bits emitted at each time instant in the same frequency band. For simplicity, we consider only square QAM modulation, indicating $\Delta b = 2$ in link adaptation algorithms. The detection technique is ZF-VBLAST except for the SVD signaling, where decoupled substreams are encountered. We also assume that the path loss from each distributed antenna is 0dB and the independent shadowing is modeled as log-normal-distributed with the standard deviation of 8dB.

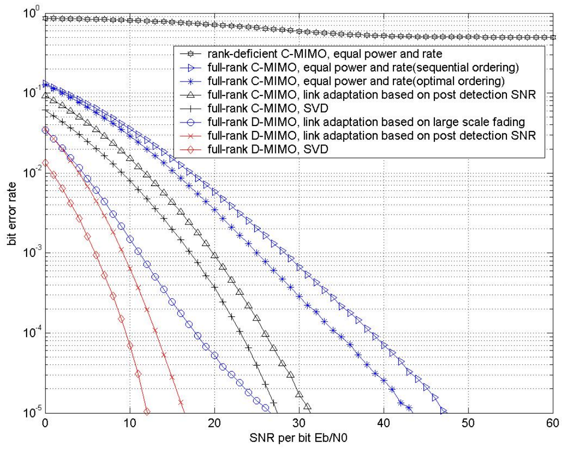

Fig.3. Performance of link adaptation in C-MIMO and D-MIMO

As we can see in Fig.3, for a rank-deficient C-MIMO(rank 2 in this case), the equal-power equal-rate signaling of the original V-BLAST exhibits much inferior performance as not all independent substreams can be recovered after passing through the channel. For a full-rank C-MIMO channel, there is a significant performance gap between V-BLAST signaling and optimal SVD (about 15 dB at a BER of 10^{-5}), indicating the advantages of having CSI at the transmitter side to enable link adaptation techniques.

The most exciting result we obtain is that link adaptation only based on macroscopic channel knowledge in D-MIMO (lower bound for link adaptation for D-MIMO) performs even better than link adaptation based on SVD in C-MIMO (upper bound for link adaptation for C-MIMO) in a large range of interest. This advantage results from the macrodiversity in D-MIMO, which is not available in a C-MIMO system. As we mentioned, this link adaptation scheme can be efficiently implemented, offering an excellent tradeoff between performance and complexity.

Note that for link adaptation based on post detection SNR, the equivalent subchannel gains vary with the detection order. However, in contrast to open loop V-BLAST, simulation shows that ordering has little influence on the performance since our power allocation scheme makes up the possible loss in the ordering. Therefore we only consider the sequential ordering during the detection. From Fig.3, we can see that performance of this link adaptation scheme closely approaches that of SVD, which also indicates little improvement will be obtained if optimal ordering is considered, since SVD signaling is the performance upper bound. On the other hand, optimal ordering deployed for the open-loop V-BLAST achieves 3-4 dB gain.

Finally, we notice that more detailed channel knowledge at the transmitter and receiver side of both D-MIMO and C-MIMO can be traded for even higher performance gain. SVD signaling scheme is the performance upper bound, but it requires feedback of the instantaneous channel information, which may consume significant system bandwidth. Link adaptation based on post detection SNR only requires CSI on the receiver side, and feeds back the information of selected link adaptation modes only when they are different from the currently used ones. The performance of this link adaptation scheme closely approaches that of SVD-based link adaptation scheme. The gap between SVD-based and post-SNR based schemes may be partly due to the error propagation in V-BLAST detection.

V. CONCLUSION

In this paper, macrodiversity inherent in D-MIMO is effectively explored to adapt the data transmission for better system performance with reasonable cost. Especially, link adaptation for D-MIMO only based on large scale fading outperforms the SVD-based link adaptation in C-MIMO in a large range of interest without incurring much system overhead. When available, more detailed channel information at the transmitter side of D-MIMO can be traded for further performance improvement.

REFERENCES

[1] P. Chow, A. Karim, V. Fung and C. Dietrich, "Performance advantages of distributed antennas in indoor wireless communication systems," *Proc.1994 Spring IEEE Vehicular Technology Conference,* pp. 1522-1526, Stockholm, Sweden, June 1994.

[2] S..Chung, A. Lozano and H.Huang, "Low complexity algorithm for rate quantization in extended V-BLAST," *Proc.2001 Fall IEEE Vehicular Technology Conference*, vol. 2, pp.910-914, Atlantic City, NJ, Oct.2001.

[3] T. Starr, J. M. Cioffi and P. J. Siverman, Understanding Digital Subscriber Line Technology, Prentice Hall, Upper Saddle River, NJ, 1999.

[4] U. Weiss, "Designing macroscopic diversity cellular systems," *Proc. 1999 Spring IEEE Vehicular Technology Conference* ,vol. 3, pp.2954-2058, Houston, TX, May 1999.

[5] P.W. Wolniansky, G.J. Foschini, G.D. Golden and R. A. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," *Proc.1998 URSI International Symposium on Signals, systems, and Electronics (ISSSE 98),* pp. 295-300, Pisa, Italy, Oct.1998.

[6] H.Zhang and H.Dai, "On the capacity of distributed MIMO systems," To appear in CISS'04, Princeton University, Princeton, NJ, March 2004.