Receive Antenna Selection for MIMO Systems in Correlated Channels

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Abstract—**Multiple-input multiple-output (MIMO) systems can provide great capacity improvement but suffer from multiple expensive RF chains. Antenna selection offers a good tradeoff between complexity and performance. This paper addresses the problem of optimal receive antenna selection in correlated channels. We consider the transmission of *M* independent signals to a base station with *N* correlated antennas and present two criteria for selecting the optimal *L* out of *N* receive antennas in terms of capacity maximization or BER minimization, assuming that only the long-term channel statistics, instead of the instantaneous channel state information, are known. Simulations will validate our theoretical analysis and demonstrate that within a rather wide angular spread range, the number of required RF chains can be significantly decreased using our proposed selection strategy while achieving very close performance to the instantaneous antenna selection system and the conventional MIMO system without antenna selection.**

Keywords- *Correlated channels, Antenna selection, MIMO systems, Channel capacity, Singular value decomposition.*

I. INTRODUCTION

MIMO (Multiple-Input Multiple-Output) systems with multiple antennas at both the transmitter and receiver can provide great capacity improvements [1-4]. However, the deployment of multiple antennas would require the implementation of multiple RF chains that are typically very expensive. Dealing with this issue, [5-7] proposed a system know as *Hybrid Selection/Maximum ratio combining* in which only *L* out of *N* antennas are effectively deployed, and only *L* RF chains are thus required. [8-9] further applied this antenna selection technique to MIMO links. Transmit [8] or receive [9] antennas are selected to maximize the channel capacity and it was shown that selecting the best antenna subset gives almost the same capacity as the conventional systems but with much less RF chains.

The above stated advantages hold unfortunately only when the channel is rich enough. Usually channel links present spatial correlation due to the lack of spacing between antennas, or to the existence of small angular spread. Both cases lead to a diminishing diversity and multiplexing gain, and this will significantly affect the capacity [10]. Numerous work have been done to combat this harmful effect using feedback at the transmitter, such as adding a linear transformation matrix [11], applying per-antenna rate and power control [12], selecting

transmit antennas [13], or jointly selecting the transmit-receive antenna pair [14]. All of these schemes aim at more efficiently designing the transmission signals or obtaining more diversity advantage so as to improve the performance under correlation. However, little work has been done to make use of the correlation to decrease the receive complexity. This paper will show that the number of RF chains at the receiver side can actually be greatly reduced with very slight performance loss in correlated channels.

We consider a narrow-band uplink communication system with *M* transmitted signals over a slowly varying flat channel, and received by *N* antennas. Since there are usually enough scatters around the mobile while at the BS the angular spread is small due to the high attitude, we assume that antenna correlation only exists at the receiver (BS) side. We present two criteria for receive antenna selection, which are based on maximizing the capacity and minimizing the bit error rate (BER), respectively. Unlike the work in [9], our receive antenna selection is only based on the long-term statistical channel knowledge, namely, the correlation matrix, instead of the instantaneous channel state information. Since the correlation matrix only changes with the antenna position patterns or the surrounding environment, such as buildings, etc., it will remain invariant for long time intervals. Thus, our proposed *correlated selection algorithm* (CSA) has the advantage of introducing further complexity reduction than the one that selects the receive antennas based on the exact channel knowledge which we refer to as *instantaneous selection algorithm* (ISA). We demonstrate that for capacity maximization, the antenna subset should be chosen to maximize the determinant of the correlation matrix, while for BER minimization, the antenna subset should be chosen to minimize the square sum of the eigenvalues of the correlation matrix. Simulation results will be used to validate our analysis and show that our selection algorithm can achieve nearly the same capacity and BER performance as ISA in correlated channels. Although with increasing angular spread the performance gap between ISA and CSA will get bigger, it is shown that within a rather wide angular spread range (1°, 60°), the capacity difference between both algorithms is lower than 1 bit/s/Hz. The comparison results between our selection system and the conventional system will also show that in correlated channels the number of selected antennas can be dramatically reduced while keeping the BER performance nearly unchanged.

This paper is organized as follows. In Section II, we provide the system model and the various notations used throughout the paper. In Section III, we derive two criteria for receive antenna selection: Capacity maximization and BER minimization, which are only related to the correlation matrix. Section IV shows the capacity and symbol error rate (SER) performance of CSA along with the comparison to ISA and the conventional system. Finally, Section VI summarizes and concludes this paper.

II. SYSTEM MODEL

We consider the transmission of M signals to a receiver with N antennas. These signals undergo a slowly Rayleigh fading channel. The channel is then assumed to be constant within a frame of T symbols. Once received, these signals are multiplexed into L RF chains, and only the best L out of N signals are selected based on some criterion for further processing and the remaining N-L receive antennas are shut down. Therefore, once selected, only L RF branches are needed and thus the complexity can be greatly decreased. For simplicity, we assume in the following a perfect channel knowledge at the receiver side only, through the use of training sequences.

Let $\mathbf{x} = [x_1, x_2, ..., x_M]^T$ denote the transmitted signal vector. Each element x_i is transmitted with the same power from the ith antenna. Also, let $\mathbf{H}$ denotes the $N \times M$ channel matrix. Assuming perfect symbol synchronization at the receiver, then the discrete model of the received complex N-length signal vector can be written as

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

where $\mathbf{n}$ denotes the complex Gaussian N-vector noise with covariance $\sigma^2 \mathbf{I}$.

Following the channel model provided in [10], the channel matrix could be written as $\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_w \mathbf{R}_t^{1/2}$, where $\mathbf{H}_w$ is an $N \times M$ complex matrix of i.i.d. zero-mean, unity variance complex Gaussian random variables. $\mathbf{R}_t$ and $\mathbf{R}_r$ denote $M \times M$ and $N \times N$ antenna correlation matrices at the transmitter and the receiver sides, respectively. In this paper, we deal only with the correlation at the receiver, and $\mathbf{H}$ is given by

$$\mathbf{H} = \mathbf{R}_r^{1/2} \mathbf{H}_w \qquad (2)$$

We define the *selected antenna subset* as Λ_L which is not an ordered set with L selected antennas. Let $\mathbf{y}_{\Lambda_L}$ be the complex data vector obtained after selection and $\mathbf{R}_{\Lambda_L}$ be the cross-correlation matrix of these L selected antennas. The latter is obtained by eliminating the columns and rows of the non-desired antennas. $\mathbf{H}_{\Lambda_L}$ represents the channel gain between M transmit antennas and the L receive antennas. Then, we have

$$\mathbf{y}_{\Lambda_L} = \mathbf{H}_{\Lambda_L} \mathbf{x} + \mathbf{n}_{\Lambda_L} = \mathbf{R}_{\Lambda_L}^{1/2} \mathbf{H}_w^{\Lambda_L} \mathbf{x} + \mathbf{n}_{\Lambda_L} \qquad (3)$$

The following notation is used throughout this paper: * for conjugate transpose, ' for transpose, $\mathbf{I}_{n \times n}$ for $n \times n$ identity matrix, $\mathbf{0}_{m \times n}$ for $m \times n$ zero matrix, $\det(\cdot)$ for determinant, $trace(\cdot)$ for trace, a_{ij} for the element in the ith row and the jth column of matrix $\mathbf{A}$.

III. ANTENNA SELECTION CRITERIA

In the following derivation, we try to separate the eigenvalues of $\mathbf{H}_w^{\Lambda_L}$ and that of the correlation matrix $\mathbf{R}_{\Lambda_r}$ so as to obtain the selected criterion which is only related to $\mathbf{R}_{\Lambda_r}$.

A. Capacity Maximization

As we know,

$$C_{\Lambda_L} = \log_2 \det(\mathbf{I}_{L \times L} + \frac{\rho}{M} \mathbf{H}_{\Lambda_L} \mathbf{H}_{\Lambda_L}^*) \qquad (4)$$

where ρ is the mean SNR per receive branch.

By applying *Singular Value Decomposition* (SVD) to $\mathbf{R}_{\Lambda_r}$, we have

$$\mathbf{R}_{\Lambda_r} = \mathbf{U}_r \mathbf{Q}_r \mathbf{U}_r^* \qquad (5)$$

where $\mathbf{U}_r$ is a unitary matrix whose columns are the eigenvectors of $\mathbf{R}_{\Lambda_r}$, and $\mathbf{Q}_r$ is a diagonal matrix whose diagonal entries are the eigenvalues of $\mathbf{R}_{\Lambda_r}$.

The capacity can then be written as

$$C_{\Lambda_L} = \log_2 \det[\mathbf{I}_{L \times L} + \frac{\rho}{M} \mathbf{U}_r \mathbf{Q}_r^{1/2} \mathbf{H}_w^{\Lambda_L} \left(\mathbf{H}_w^{\Lambda_L}\right)^* \mathbf{Q}_r^{1/2} \mathbf{U}_r^*] \qquad (6)$$

$$= \det[\mathbf{I}_{L \times L} + \mathbf{Q}_r \mathbf{W}]$$

where $\mathbf{W} = \frac{\rho}{M} \mathbf{H}_w^{\Lambda_L} \left(\mathbf{H}_w^{\Lambda_L}\right)^*$. $\qquad (7)$

Assume that $\mathbf{Z}$ is an $L \times L$ diagonal matrix with the diagonal elements z_{ii}'s, where

$$z_{ii} = \begin{cases} \frac{\rho}{M} d_{\Lambda_L}^{(1)} & i = 1, ..., M \\ 1 & i = M+1, ..., L \end{cases}$$

, $d_{\Lambda_L}^{(k)}$'s are descending sorted eigenvalues of $\mathbf{H}_w^{\Lambda_L} \left(\mathbf{H}_w^{\Lambda_L}\right)^*$, for $k = 1, ..., M$. Therefore $d_{\Lambda_L}^{(1)}$ is the maximum eigenvalue of $\mathbf{H}_w^{\Lambda_L} \left(\mathbf{H}_w^{\Lambda_L}\right)^*$.

We present the following lemma.
Lemma 1: Assume that $\mathbf{A}$ is an arbitrary $n \times m$ matrix with non-negative eigenvalues and $\mathbf{B}$ is an $n \times n$ non-negative definite diagonal matrix with $m \leq n$. Then,
$$\lambda_i(\mathbf{A}^* \mathbf{B} \mathbf{A}) \leq \lambda_1(\mathbf{A} \mathbf{A}^*) \lambda_i(\mathbf{B}), \ i = 1, ..., m.$$

With the above lemma, it is clear that $z_{ii} \geq \lambda_{\mathbf{W}}^{(i)}$, $i = 1, ..., L$, where $\lambda_{\mathbf{W}}^{(i)}$'s are the eigenvalues of $\mathbf{W}$, $i = 1, ..., L$.

If $\mathbf{A}$ and $\mathbf{B}$ are both $n \times n$ Hermitian non-negative definite matrix, and $\mathbf{A} \geq \mathbf{B}$ (i.e., $\mathbf{A} - \mathbf{B} \geq \mathbf{0}$), then $\det(\mathbf{A}) \geq \det(\mathbf{B})$. Hence, given that $\mathbf{Z} \geq \mathbf{W}$, we have

$$\det[\mathbf{I}_{L \times L} + \mathbf{Q}_r \mathbf{W}] \leq \det[\mathbf{I}_{L \times L} + \mathbf{Q}_r \mathbf{Z}] = \prod_{i=1}^{L} (1 + q_{\Lambda_L}^{(i)} z_{ii}) \qquad (8)$$

where $q_{\Lambda_L}^{(i)}$'s are the descending sorted eigenvalues of $\mathbf{R}_{\Lambda_r}$, for $i = 1, ..., L$.

For high ρ, we can make the following approximation:

$$\prod_{i=1}^{L}(1+q_{\Lambda_L}^{(i)} z_{ii}) \approx \left(\frac{\rho}{M}\right)^M \left(d_{\Lambda_L}^{(1)}\right)^M \prod_{i=1}^{L} q_{\Lambda_L}^{(i)} \quad (9)$$

As a result, we can get

$$C_{\Lambda_L} \le M \log_2\left(\frac{\rho}{M}\right) + M \log_2\left(d_{\Lambda_L}^{(1)}\right) + \log_2\left(\prod_{i=1}^{L} q_{\Lambda_L}^{(i)}\right) \quad (10)$$

Therefore, to maximize the capacity upper bound, we should maximize the determinant of $\mathbf{R}_{\Lambda_L}$, namely, $\prod_{i=1}^{L} q_{\Lambda_L}^{(i)}$. Define

$$\xi_{\Lambda_L}^C = \prod_{i=1}^{L} q_{\Lambda_L}^{(i)} \quad . \quad (11)$$

Then, our capacity maximization criterion can be written as follows.

Proposition 1: *For a given L, the optimal selected antenna subset Λ_L^* that maximizes the capacity is given by*

$$\Lambda_L^* = \arg\max_{\Lambda_L} \xi_{\Lambda_L}^C \quad (12)$$

where $\xi_{\Lambda_L}^C$ is given by (11).

B. BER minimization

Assume that the zero forcing based detector is employed. Then, the decorrelating matrix can be written as

$$\mathbf{G} = \left(\mathbf{H}_L^* \mathbf{H}_L\right)^{-1} \mathbf{H}_L \quad (13)$$

Next, assume that $\mathbf{\omega_i} = [g_{i1}, g_{i2}, ..., g_{iM}]$, then the receive SNR of the ith stream is $(\rho/M)/\|\mathbf{\omega_i}\|^2$.

We would like to minimize the worst BER. This is equivalent to maximization of the minimum receive SNR, namely,

$$\max\left\{\min_i\left(1/\|\mathbf{\omega_i}\|^2\right)\right\} \quad (14)$$

Given that $\|\mathbf{\omega_i}\|^2 = \bar{\mathbf{g_i}}\cdot\bar{\mathbf{g_i}}^* = \left(\mathbf{G}\cdot\mathbf{G}^*\right)_{i,i} = \mathbf{J}_{i,i}$, where $\mathbf{J} = (\mathbf{H}_L^* \mathbf{H}_L)^{-1}$. Then, (14) is equivalent to

$$\min\left\{\max_i \mathbf{J}_{i,i}\right\} \quad (15)$$

We can further derive that

$$\max_i \mathbf{J}_{i,i} \le \sum_{i=1}^{M} \lambda_i^{-1} \le \frac{1}{q_{\Lambda_L}^{(L)}} \cdot \left(\frac{M}{\sum_{i=1}^{M} d_{\Lambda_L}^{(i)}} + \frac{M-1}{d_{\Lambda_L}^{(M)}}\right) \quad (16)$$

where λ_i's are the eigenvalues of $\mathbf{H}_{\Lambda_L} \mathbf{H}_{\Lambda_L}^*$.

From (16) it is clear that the upper bound of BER is dependent on $q_{\Lambda_L}^{(L)}$ which is the minimum eigenvalue of $\mathbf{R}_{\Lambda_L}$. Thus, if we define

$$\xi_{\Lambda_L}^{BER} = q_{\Lambda_L}^{(L)} = \min_{i=1,...,L} q_{\Lambda_L}^{(i)} \quad (17)$$

Then, according to (16), our BER minimization criterion can be written as follows.

Proposition 2: *For a given L, the optimal selected antenna subset Λ_L^* that minimizes the BER is given by*

$$\Lambda_L^* = \arg\max_{\Lambda_L} \xi_{\Lambda_L}^{BER} \quad (18)$$

where $\xi_{\Lambda_L}^{BER}$ is given by (17).

We conclude this selection by summarizing our selection algorithm, which we refer to as CSA. For simplicity, we take the example of capacity maximization. The description of CSA for BER minimization is similar.

ALGORITHM I

CORRELATED SELECTION ALGORITHM (CSA)

(i)	Let $K = C_N^L$.
	Initialization: Set $\xi^C = 0$, $\Lambda_L^* = \mathbf{0}_{L\times 1}$, and generate all possible Λ_L's: $\Lambda_L^{(1)}$, $\Lambda_L^{(2)}$, ..., $\Lambda_L^{(K)}$.
(ii)	For $m = 1$ to K,
	Compute $\xi_{\Lambda_L^{(m)}}^C$ for each $\Lambda_L^{(m)}$.
	If $\xi_{\Lambda_L^{(m)}}^C \ge \xi^C$, then
	$\Lambda_L^* = \Lambda_L^{(m)}$, $\xi^C = \xi_{\Lambda_L^{(m)}}^C$.
	End if.
	End loop
(iii)	Output Λ_L^*.

IV. SIMULATION RESULTS

In this section, we present simulation results that validate the criteria derived in the previous propositions. We will also compare the performance between our selection scheme CSA and ISA. Performance is evaluated in terms of capacity and symbol error rate (SER) for a frame of 200 symbols from QPSK constellations averaged over 5000 frames. We consider an uncoded system with $M = 2$ transmit antennas and $N = 6$ receive antennas. We adopt the correlated channel model described in [10,15]. Linear arrangement of the antenna array is assumed at the receiver (BS side) with the antenna separation being 4 wavelengths. We also assume the "broadside" case as defined in [10], and that the incoming waves are uniformly distributed in the angular spread Δ [14].

A. Theoretical results validation

In order to show the validity of our criteria, we use Monte Carlo simulations to decide which L antennas should be selected. For every possible antenna subset Λ_L, we compute its corresponding capacity or SER and select the one that has the best performance. Table I presents a sample of the comparison results under different angular spreads and different number of selected antennas. We label the receive antennas as 1, 2, ... , 6. We also notice that the optimal antenna subset Λ_L^* obtained using the theoretical criteria as described in the propositions may not be unique. For example, for $\Delta = 5^\circ$ and $L = 3$, Subset $\Lambda_L^{(1)} = \{1, 2, 6\}$ and Subset $\Lambda_L^{(2)} = \{1, 5, 6\}$ have $\xi_{\Lambda_L^{(1)}}^C = \xi_{\Lambda_L^{(2)}}^C$. Thus, both subsets are optimal in terms of capacity maximization. We computed their

corresponding capacity using Monte Carlo simulations and found the difference between their corresponding capacity values to be within 2%. Therefore, in the "Simulation" column we also list both subsets. From Table I, it is obvious that the theoretical results coincide very well with the simulation results, thus, verifying the validity of our criterion.

TABLE I. SELECTION RESULTS USING THE PROPOSED SELECTION SCHEME AND MONTE CARLO SIMULATION WHEN $N=6$ AND $M=2$

Δ	L	Theory		Simulation (SNR=16dB)	
		Capacity max.	BER min.	Capacity max.	BER min.
5°	2	{1, 6}	{1, 6}	{1, 6}	{1, 6}
	3	{1, 2, 6} or {1, 5, 6}	{1, 2, 6} or {1, 5, 6}	{1, 2, 6} or {1, 5, 6}	{1, 2, 6} or {1, 5, 6}
	4	{1, 2, 5, 6}	{1, 2, 5, 6}	{1, 2, 5, 6}	{1, 2, 5, 6}
45°	2	{1, 6}	{1, 6}	{1, 6}	{1, 6}
	3	{1, 3, 6} or {1, 4, 6}	{1, 3, 6} or {1, 4, 6}	{1, 3, 6} or {1, 4, 6}	{1, 3, 6} or {1, 4, 6}

B. Performance comparison for different L under given Δ

According to the above criteria, with a given L, we can easily select the "best" receive antennas. Fig. 2 and Fig. 3 show the cumulative distribution function (cdf) of the capacity and SER of our selection algorithm CSA for different values of L under a given angular spread Δ, respectively. For comparison, the performance of ISA is also presented. In ISA, for every realization of the channel matrix **H**, a complete set of all the possible matrices $\tilde{\mathbf{H}}$ is created by eliminating all possible permutations of N-L rows from the matrix. Then, for each $\tilde{\mathbf{H}}$, the capacity (or SER) is computed and the best one from the set is selected.

Fig. 1 presents the capacity cdf curves of CSA and ISA with L ranging from 2 to 4 and the angular spread being 5° and 45° with SNR 16dB. We can see that when $\Delta = 5°$, CSA can achieve nearly the same capacity as ISA. Actually, such a low angular spread implies a fully correlated channel, which means that the receive correlation effect dominates the whole channel. Hence, a selection based on the correlation matrix will not result in any performance degradation compared with that based on the instantaneous channel state information. However, with the increase of angular spread, the effect of the correlation will weaken and ISA's advantage over CSA becomes more and more significant. As Fig. 1 shows, when Δ increases to 45°, the 10% outage capacity of ISA is at least 1.8 bit/s/Hz larger than CSA for L=2 case. However, with a larger value of L, the capacity difference decreases greatly. As a comparison, we also plot the capacity cdf curves of the conventional system without receive selection (L=N=6).
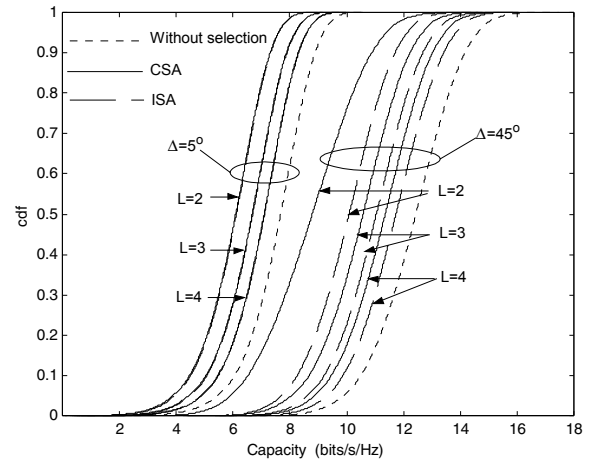

Fig. 1: Capacity cdf of CSA, ISA, and the conventional system with different values of L and Δ, SNR=16dB

Fig. 2 compares the SER performance of CSA and ISA. Similar to the above conclusions, we can see that with a small Δ, their performance are nearly the same, while with increasing Δ, the performance gap increases. However, there are two key observations. First, in Fig. 1 it can be observed that no matter whether CSA or ISA is adopted, the capacity loss is significant compared with the conventional system. While from Fig. 2, we can see that for a low Δ, CSA with L=2 can achieve the same performance as the conventional one. This implies that with much fewer selected antennas, we can keep the SER performance nearly unchanged. Therefore, *in correlated channels, the receiver complexity can be decreased greatly with very slight performance loss*. Second, when the angular spread increases, L should also increase to achieve good performance. Otherwise, a small L will lead to severe performance degradation. In the following sub-section, we specify L to be equal to the rank of the correlation matrix $\mathbf{R}_r$ and we will see that within a rather wide angular spread range ($\Delta = [1°, 60°]$), CSA can achieve very close performance to ISA and even the conventional system.
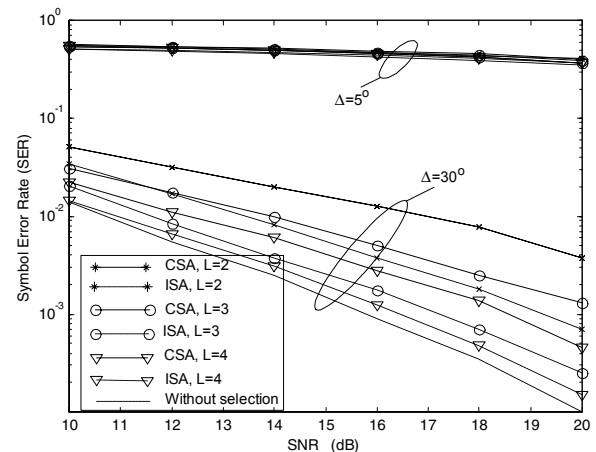

Fig. 2: SER vs. SNR curves of CSA, ISA, and the conventional system with different values of L and Δ

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C. Performance comparison for different Δ under given L

In Fig. 3 and Fig. 4, the 10% outage capacity curves and SER curves with different degrees of spatial correlation (Δ ranging from $1°$ to $90°$) are plotted. SNR is assumed to be 16dB. It can be seen that CSA can always achieve nearly the same capacity as ISA and very close SER performance to the conventional system. However, with increasing Δ, the required number of selected antennas L, which is set to be equal to the rank of the correlation matrix $\mathbf{R_r}$, also increases. In particular, when Δ is larger than $60°$, the correlation matrix is approaching $\mathbf{I_{N \times N}}$. This means that the channel is close to the uncorrelated case. As a result, CSA is not effective any more since it selects nearly all the receive antennas so as to keep good performance. Nevertheless, within a rather wide range ($\Delta = [1°, 60°]$), using CSA the system complexity can be decreased greatly while keeping a close performance to ISA and even the conventional system.
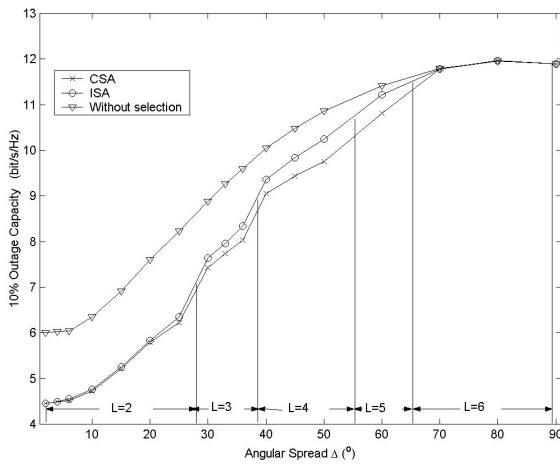

Fig. 3: Capacity vs. angular spread curves for CSA, ISA and the conventional system. SNR=16dB
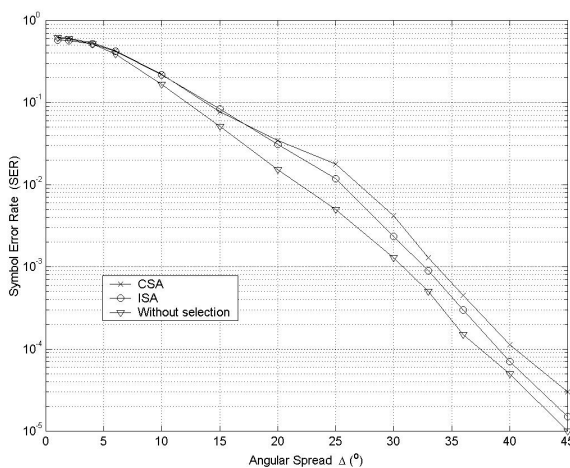

Fig. 4: SER vs. angular spread curves for CSA, ISA and the conventional system. SNR=16dB

V. CONCLUSIONS

In this paper, we derived the capacity maximization and BER minimization criterion for receive antenna selection, according to the receive antenna correlation matrix only. We showed that in correlated channels, our algorithm, which we refer to as the CSA scheme, can achieve nearly the same capacity and BER performance as the ISA scheme which selects the receive antennas based on the exact channel state information while dramatically decreasing the complexity since only the correlation matrix is needed for selection. It is also shown that within a rather wide angular spread range, the required number of RF chains when the CSA scheme is employed can be significantly decreased while achieving very close performance as the conventional system.

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