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Research Article

A Fast Adaptive Receive Antenna Selection Method in MIMO System

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Antenna selection has been regarded as an effective method to acquire the diversity benefits of multiple antennas while potentially reduce hardware costs. This paper focuses on receive antenna selection. According to the proportion between the numbers of total receive antennas and selected antennas and the influence of each antenna on system capacity, we propose a fast adaptive antenna selection algorithm for wireless multiple-input multiple-output (MIMO) systems. Mathematical analysis and numerical results show that our algorithm significantly reduces the computational complexity and memory requirement and achieves considerable system capacity gain compared with the optimal selection technique in the same time.

1. Introduction

Multiple-input multiple-output (MIMO) wireless systems which are characterized by multiple transceiver antenna elements have been already widely used in modern communication. MIMO technique has demonstrated the potential capability for capacity increasing in rich multipath environments, for example, urban macrocell scenario, without any increase in bandwidth or transmit power [1–3]. MIMO systems require additional antenna elements compared to traditional SISO systems. These additional antenna elements, for example, patch or dipole antennas, and the additional digital signal processing are usually not of high cost; however, the RF elements which include low-noise amplifiers, down converters, and analog-to-digital (AD/DA) converters are expensive because those elements do not follow Moore's law. To reduce hardware costs, antenna selection has been proposed in [4–6] as an attractive low-cost and low-complexity technique. The key idea of this technique is choosing a subset of the available transmit and/or receive antennas as optimal as possible.

Experimental investigation shows that with proper diversity and coding scheme the choosing optimal antenna subset can also achieve almost full diversity gain; this means that antenna selection scheme can take most of the advantages of MIMO systems while simultaneously reducing hardware costs of all systems. Furthermore, with the same number of RF chains, a MIMO system which uses antenna selection has been shown to achieve significant perform gain compared with a system without using antenna selection. There are many strategies of antenna selection scheme, for example; from the aspect of antenna selection process, it can be divided into "Globe" [7] and "Local," and from the aspect of terminal, it can be divided into transmit antenna selection [8–10] and receive antenna selection. In this paper we are focused on the research of local receive antenna selection scheme.

An optimal antenna selection scheme is proposed in [11, 12] which realizes through an exhaustive search overall possible antenna subsets. Numerical results show that the computational complexity of this scheme increases exponentially with the available antenna numbers. Furthermore, if the channel state information (CSI) changes rapidly, the computational cost and delay of reselection are intolerable in realistic real-time communication system. To reduce the computational complexity of antenna selection and fulfill the practical requirement of real-time system, in recent years, considerable works and theoretical investigations have been done to solve the trade-off problem between performance and complexity. A fast antenna selection scheme has been proposed in [13], which simply chooses the antenna that has

the largest Euclidean norms. We will refer to this simple fast algorithm as the norm-based selection (NBS) method. Though reducing the computational complexity significantly, this strategy simultaneously gives rise to performance loss. Therefore, as a MIMO system is mainly focused on realization complexity, system capacity, and bit error rate, a fast but also maintain considerable capacity antenna selection algorithm is most desirable for practical application.

Gorokhov [14] proposed a promising method for the antenna subset selection. This algorithm generates a near-optimal selection subset of receive antennas based on maximum capacity. It starts with the full set of receive antennas and then removes one antenna per step. The selection criterion of this algorithm is removing the antenna with the lowest contribution to the system capacity which is calculated by a proper updating formula. In contrast to [14], the algorithm proposed by Gharavi-Alkhansari and Gershman in [15] starts with the empty set of receive antennas and adds one antenna per step. These two selection processes are repeated until the required numbers of antennas are obtained. One question is that traditional antenna selection algorithms are failed to consider the proportion between N_L and N_R (which represent the numbers of selected antennas and total receive antennas) which will increase the computational complexity if inappropriate scheme has been used in MIMO system. As more and more techniques are aimed at improving the received SNR, another question is whether the antenna selection scheme will change in moderate and high SNR regions. This needs from us to find an appropriate system model and improve the existing achievements.

In this paper we propose an improved fast adaptive antenna selection algorithm. The contributions of this paper are as follows. Firstly, the system model is improved, and the details of system capacity calculation method are shown in system model part; our proposed system model fits moderate and high received SNR regions better. Secondly, in order to reduce the computational complexity and the memory requirement in each step of selection, we improve the update formulas of variables which will be used in our proposed scheme based on the novel system model and Sherman-Morrison formula. Lastly, the proposed algorithm also adaptively optimizes the antenna selection process according to the proportion between the numbers of total receive antennas and selected antennas which steps further in reducing the complexity of whole process.

Numerical results show that our algorithm gets better system performance than simple norm-based selection method [13] and the selection method in [14, 15] both in moderate and high SNR situations.

This paper is organized as follows. In Section 2, the MIMO system signal model is formulated. In Section 3, our novel antenna selection algorithm is proposed. Section 4 gives the simulation results and compares our algorithm with others. Finally, conclusions are drawn in Section 5.

2. MIMO System Signal Model

The antenna configuration of MIMO system is shown in Figure 1. The purpose of antenna selection algorithm is to choose N_L from N_R antennas by adding or removing one antenna per step.

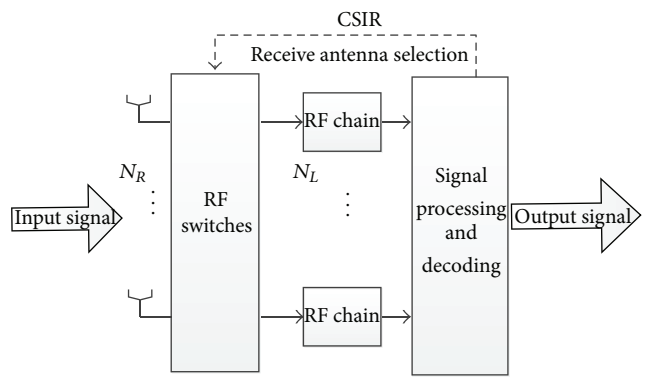

Figure 1: Receive antenna selection configuration.

The signal model of this system is given by

$$y = Hx + n, \tag{1}$$

where x denotes the $N_T \times 1$ transmitted signal vector, y denotes the $N_R \times 1$ received signal vector, and n denotes the $N_R \times 1$ receiver noise vector. We assume that the noise at receive ends is represented by independent and zero-mean circularly symmetric complex Gaussian random variables. $N_R \times N_T$ matrix H is the channel matrix of the MIMO system in which element $H_{i,j}$ represents the complex gain of the channel between the jth transmit antenna and the ith receive antenna. The elements of H are represented by independent complex Gaussian random variables with zero mean and unit variance (e.g., Rayleigh fading channel model).

It is assumed that channel matrix H is perfectly known at the receiver and is completely unknown at the transmitter. Therefore, each transmitting antenna gets equal power. The capacity of this $N_R \times N_T$ MIMO system can be expressed as

$$C = \log_2 \det\left(I_{N_T} + \frac{\rho}{N_T} H^H H\right), \tag{2}$$

where I_{N_T} denotes an $N_T \times N_T$ identity matrix, ρ is the average SNR at the receiver, $\det(\cdot)$ is the matrix determinant, and $(\cdot)^H$ stands for the Hermitian transpose. As each step of antenna selection is realized at the receiver to choose the most suitable propagation path which maximizes the system capacity, the capacity after step n can be written as

$$\widehat{C_n} = \log_2 \det\left(I_{N_T} + \frac{\rho}{N_T} \widehat{H}_n^H \widehat{H}_n\right), \tag{3}$$

where $\widehat{H}_n$ is a submatrix of the original channel matrix H. The dimension of $\widehat{H}_n$ depended on whether the antenna selection algorithm adds or removes one antenna per step; for example, for step n, it can be $n \times N_T$ or $(N_R - n) \times N_T$. The question here is to find the best submatrix $\widehat{H}_n$ which maximizes system capacity:

$$\widehat{H}_n : \max_{\widehat{H}_n} \log_2 \det\left(I_{N_T} + \frac{\rho}{N_T} \widehat{H}_n^H \widehat{H}_n\right). \tag{4}$$

In traditional antenna selection scheme such as [14, 15], the antenna selection criterion is represented as (4), which means that these schemes make submatrix $\widehat{H}_n$ in keeping with (4) by choosing or removing one antenna in each step. As new communication technologies have been proposed in recent years, some of them are aimed at improving the received SNR. We wonder if we can improve the system model to make it more suitable for moderate and high SNR regions.

Note that

$$\det\left(I_{N_T}+\frac{\rho}{N_T}\widehat{H}_n^H\widehat{H}_n\right)=\prod_{i=1}^{n \text{ or } N_R-n}\left(1+\frac{\rho}{N_T}\sigma_i^2\right),$$
$$\widehat{C}_n=\sum_{i=1}^{n \text{ or } N_R-n}\log_2\left(1+\frac{\rho}{N_T}\sigma_i^2\right), \tag{5}$$

where σ_i, $i=1,2,3\ldots,n$ or N_R-n are the nonzero singular values of channel matrix $\widehat{H}_n$ after the antenna selection in each step. Therefore, for moderate and high SNR situations, the channel capacity can be rewritten as

$$\begin{aligned}\widehat{C}_n &\approx (n \text{ or } N_R-n)\log_2\left(\frac{\rho}{N_T}\right)+\sum_{i=1}^{n \text{ or } N_R-n}\log_2\sigma_i^2\\ &=(n \text{ or } N_R-n)\log_2\left(\frac{\rho}{N_T}\right)+\log_2\prod_{i=1}^{n \text{ or } N_R-n}\sigma_i^2\\ &=(n \text{ or } N_R-n)\log_2\left(\frac{\rho}{N_T}\right)+\log_2\left(\det\left[\widehat{H}_n^H\widehat{H}_n\right]\right).\end{aligned} \tag{6}$$

In our proposed receive antenna selection scheme, the system model is improved as (6). It can be concluded that, whether adding or removing one antenna per step, the final purpose of our scheme is to find the best submatrix $\widehat{H}_n$ in each step based on

$$\widehat{H}_n : \max_{\widehat{H}_n}\det\left[\widehat{H}_n^H\widehat{H}_n\right]. \tag{7}$$

Compared with (4), it is obviously to draw a conclusion that our scheme has lower computational complexity and fits moderate and high SNR regions better. After antenna selection processing, the dimension of chosen submatrix $\widehat{H}$ is $N_L\times N_T$.

3. Proposed Algorithm

The proposed algorithm firstly compares the sizes of N_L and N_R, and then it can be divided into two parts based on the system model proposed in Section 2.

3.1. Selected Antennas Are Less Than Half of Total Receive Antennas. Which means $2N_L<N_R$, the proposed algorithm will start with the empty set of selected antennas and then add one antenna per step to this set. In this situation, $\widehat{H}_n$ contains n rows of H, which represent the n antennas selected by last n step; the dimension of $\widehat{H}_n$ is $n\times N_T$. We denote the ith row of H by r_i and its Hermitian transpose by h_i.

It is assumed that in the next $(n+1)$th step the selected antenna is the ith row of H, and this antenna will be added to $\widehat{H}_n$. We get new channel submatrix $\widehat{H}_{n+1}$, whose dimension is $(n+1)\times N_T$. Then, using (6), we have

$$\widehat{C}_{n+1}=(n+1)\log_2\left(\frac{\rho}{N_T}\right)+\log_2\left(\det\left[\widehat{H}_{n+1}^H\widehat{H}_{n+1}\right]\right). \tag{8}$$

The relationship between r_i and $\widehat{H}_{n+1}$ has been given in [11], which can be expressed as

$$\widehat{H}_{n+1}^H\widehat{H}_{n+1}=\widehat{H}_n^H\widehat{H}_n+h_ih_i^H. \tag{9}$$

Moreover, Sherman-Morrison formula for determinants shows that

$$\left(A+uv^H\right)^{-1}=A^{-1}-\frac{A^{-1}uv^HA^{-1}}{1+v^HA^{-1}u}. \tag{10}$$

Bringing (9)-(10) into (8), we get

$$\widehat{C}_{n+1}=\widehat{C}_n+\log_2\left(\frac{\rho}{N_T}\right)+\log_2\left(1+h_i^H\left(\widehat{H}_n^H\widehat{H}_n\right)^{-1}h_i\right). \tag{11}$$

Define

$$A_n=\left(\widehat{H}_n^H\widehat{H}_n\right)^{-1}, \tag{12}$$

$$\beta_{i,n}=h_i^H\left(\widehat{H}_n^H\widehat{H}_n\right)^{-1}h_i=h_i^HA_nh_i. \tag{13}$$

Formula (11) can be rewritten as

$$\widehat{C}_{n+1}=\widehat{C}_n+\log_2\left(\frac{\rho}{N_T}\right)+\log_2\left(1+\beta_{i,n}\right), \tag{14}$$

where $\beta_{i,n}$ represents the size of increased capacity to the MIMO system which is brought by adding the selected antenna i into $\widehat{H}_n$ in $(n+1)$th step. The criterion that which antenna I will be chosen is

$$I=\arg\max_i\beta_{i,n}. \tag{15}$$

Using Sherman-Morrison formula, matrix A_n can be updated as

$$\begin{aligned}A_{n+1}&=A_n-\frac{1}{1+\beta_{i,n}}A_nh_ih_i^HA_n\\ &=A_n-bb^H.\end{aligned} \tag{16}$$

Define

$$b=\frac{1}{\sqrt{1+\beta_{i,n}}}A_nh_i. \tag{17}$$

To reduce the computational complexity, the following update equation is used

$$\begin{aligned}\beta_{i,n+1}&=h_i^HA_{n+1}h_i\\ &=h_i^H\left(A_n-bb^H\right)h_i\\ &=\beta_{i,n}-\left|b^Hh_i\right|^2.\end{aligned} \tag{18}$$

This selection processing circulates until n is equal to N_L.

(1) $2N_L < N_R\ (N_R, N_L, N_T, h_1, h_2, \ldots, h_N)\ \Gamma = \phi, \Omega = \{1, 2, \ldots, N_R\}$
(2) for $i = 1$ to N_R
(3) $\quad \beta_{i,1} = h_i^H h_i$ $\qquad O(N_T N_R)$
(4) end
(5) for $n = 1$ to N_L
(6) $\quad I = \underset{i \in \{\Omega - \Gamma\}}{\operatorname{argmax}} \beta_{i,n}$ $\qquad O(N_R N_L)$
(7) $\quad A_1 = \left(h_I h_I^H\right)^{-1}$
(8) $\quad \Gamma = \Gamma + \{I\}$
(9) $\quad$ if $n < N_L$
(10) $\quad\quad b = \dfrac{1}{\sqrt{1 + \beta_{I,n}}} A_n h_I$ $\qquad O(N_T^2 N_L)$
(11) $\quad\quad A_{n+1} = A_n - bb^H$
(12) $\quad\quad$ for all $I \in \{\Omega - \Gamma\}$ $\qquad O(N_T^2 N_L)$
(13) $\quad\quad\quad \beta_{i,n+1} = \beta_{i,n} - \left|b^H h_i\right|^2$ $\qquad O(N_T N_R N_L)$
(14) $\quad\quad$ end
(15) $\quad$ end
(16) end
(17) return Γ

Algorithm 1: Selected antenna numbers are less than half of total receive antenna numbers.

3.2. Selected Antennas Are More Than Half of Total Receive Antennas. Which means $2N_L > N_R$, the proposed algorithm will start with the full set of selected antennas and then remove one antenna per step to this set. In this situation, $\widehat{H}_n$ contains $(N_R - n)$ rows of H, which represent the $(N_R - n)$ antennas that remained after last n steps; the dimension of $\widehat{H}_n$ is $(N_R - n) \times N_T$. We denote the ith row of H by r_i and its Hermitian transpose by h_i.

It is assumed that in the next $(n + 1)$th step, the selected antenna is the ith row of $\widehat{H}_n$, and this antenna will be removed from $\widehat{H}_n$. We get new channel submatrix $\widehat{H}_{n+1}$, whose dimension is $[N_R - (n + 1)] \times N_T$. In contrast to the algorithm mentioned previously, the relationship between r_i and $\widehat{H}_{n+1}$ can be expressed as

$$\widehat{H}_{n+1}^H \widehat{H}_{n+1} = \widehat{H}_n^H \widehat{H}_n - h_i h_i^H. \tag{19}$$

We can also get

$$\widehat{C}_{n+1} = \widehat{C}_n - \log_2\left(\frac{\rho}{N_T}\right) + \log_2\left(1 - h_i^H \left(\widehat{H}_n^H \widehat{H}_n\right)^{-1} h_i\right). \tag{20}$$

Using (12)-(13), formula (20) can be rewritten as

$$\widehat{C}_{n+1} = \widehat{C}_n - \log_2\left(\frac{\rho}{N_T}\right) + \log_2\left(1 - \beta_{i,n}\right), \tag{21}$$

where $\beta_{i,n}$ represents the size of decreased capacity to the MIMO system which is brought by removing the selected antenna i from $\widehat{H}_n$ in $(n + 1)$th step. The criterion that which antenna I will be chosen is

$$I = \arg\min_i \beta_{i,n}. \tag{22}$$

However, using (10) (12) (17) (19) matrix A_n can be updated as

$$\begin{aligned} A_{n+1} &= A_n + \frac{1}{1 + \beta_{i,n}} A_n h_i h_i^H A_n \\ &= A_n + bb^H. \end{aligned} \tag{23}$$

Furthermore, in this situation the updated formula of $\beta_{i,n}$ is

$$\begin{aligned} \beta_{i,n+1} &= h_i^H A_{n+1} h_i \\ &= h_i^H \left(A_n + bb^H\right) h_i \\ &= \beta_{i,n} + \left|b^H h_i\right|^2. \end{aligned} \tag{24}$$

Our proposed algorithm is suitable for any number of selected antennas. For example, if $N_R = 8$ and $N_L = 2$, the algorithm in [14] needs 6 steps to obtain the set of selected antennas and the algorithm in [15] needs 2 steps to obtain it, and if $N_R = 8$ and $N_L = 6$, the algorithm in [14] needs 2 steps to obtain it while the algorithm in [15] needs 6 steps. In these two different situations, our proposed algorithm only needs 2 steps to obtain the set of selected antennas.

The detailed steps and the computational complexity of our proposed algorithm have been shown in Algorithms 1 and 2. In this paper, the computational complexity of each step is regarded as the number of multiplication times of matrix elements, and it is multiplied by loop times to obtain the final complexity results which are shown in the right column of Algorithms 1 and 2. For example, in Algorithm 1, from steps (5) to (16) the loop times are N_L, while the dimension of A_n, h_i, and b is $N_T \times N_T$, $N_T \times 1$ and $N_T \times 1$; therefore in step (10) and (11), computational complexity is

$$\underset{\text{(Multiplication times}}{N_T \times N_T} \times \underset{\text{Loop times)}}{N_L} = {N_T}^2 N_L. \tag{25}$$

(1) $2N_L > N_R\ (N_R, N_L, N_T, h_1, h_2, \ldots, h_N)\ \Gamma = \{1, 2, \ldots, N_R\}$
(2) for $i = 1$ to N_R
(3) $\quad \beta_{i,1} = h_i^H h_i$ $\qquad O(N_T N_R)$
(4) end
(5) $A_1 = \left(H^H H\right)^{-1}$
(6) for $n = 1$ to $(N_R - N_L)$
(7) $\quad I = \underset{i \in \Gamma}{\operatorname{argmin}} \beta_{i,n}$ $\qquad O(N_R(N_R - N_L))$
(8) $\quad \Gamma = \Gamma - \{I\}$
(9) $\quad$ if $n < (N_R - N_L)$
(10) $\quad\quad b = \dfrac{1}{\sqrt{1 + \beta_{I,n}}} A_n h_I$ $\qquad O(N_T^2(N_R - N_L))$
(11) $\quad\quad A_{n+1} = A_n + bb^H$ $\qquad O(N_T^2(N_R - N_L))$
(12) $\quad\quad$ for all $I \in \Gamma$
(13) $\quad\quad\quad \beta_{i,n+1} = \beta_{i,n} + \left|b^H h_i\right|^2$ $\qquad O(N_T N_R(N_R - N_L))$
(14) $\quad\quad$ end
(15) $\quad$ end
(16) end
(17) return Γ

Algorithm 2: Selected antenna numbers are more than half of total receive antenna numbers.

The complexity of other steps can be obtained in a similar way.

As a conclusion, if selected antenna numbers, are less than half of total receive antenna numbers then the overall order of complexity is

$$O\left(\max\left\{N_T, N_R\right\} N_T N_L\right). \tag{26}$$

Otherwise it is

$$O\left(\max\left\{N_T, N_R\right\} N_T \left(N_R - N_L\right)\right). \tag{27}$$

The memory requirement of our algorithm is $O(N_R + N_T^2)$. It is obvious that the upper bound computational complexity is $O(\max\{N_T, N_R\} N_T N_R/2)$, while the computational complexity of antenna selection scheme in [15] is $O(\max\{N_T, N_R\} N_T N_L)$ which is a linear function of N_L. The reduction is due to the fact that our algorithm adaptively optimizes the antenna selection process according to the proportion between the numbers of total receive antennas and selected antennas and obtains the minimum selection steps.

4. Simulation Results

In order to show the advantages of our proposed antenna selection algorithm, we use link level simulation method to get the simulation results and compare the system capacities of our scheme and the NBS method, the fast algorithm in [15] which is called increasing antenna selection (IAS), algorithm in [14] which is called decreasing antenna selection (DAS), and the optimal antenna selection method. As we mentioned before, the elements of H are represented by independent complex Gaussian random variables with zero mean and unit variance, which means that we consider the channel as Rayleigh channel model in all cases. Different amounts of transmit and receive antennas are assumed to prove that our algorithm is suitable for large or low N_L situation, and all simulated points are obtained by averaging almost 5000 channel realizations. The CDF curves of system capacity with different SNR configuration are got through computer simulations. Table 1 shows the configuration details of each figure in our link level simulation.

Table 1: Simulation details.

Figure number	Figure 2	Figure 3	Figure 4	Figure 5
N_T	2	2	8	8
N_R	10	10	10	10
N_L	2	2	8	8
SNR (dB)	6	30	6	30
Number of terminals	5000			
Channel model	Rayleigh fast fading channel model			

Figure 2 shows the CDF curves of system capacity for SNR = 6 dB with $N_T = 2$, $N_R = 10$, and $N_L = 2$ antenna configurations and different antenna selection schemes. Figure 3 shows this curve for SNR = 30 dB with the same antenna configurations. Because $2N_L < N_R$, in these two cases, the proposed algorithm starts selecting receive antennas with the empty set and takes two steps to obtain the selected result in which DAS needs eight steps. As NBS scheme has the lowest computational complexity, it obtains the worst performance. We can see that our algorithm achieves better system performance than IAS and DAS; it also obtains closer curve to the optimal one with higher SNR.

Figures 4 and 5 show the CDF curves of system capacity for SNR = 6 dB and 30 dB with $N_T = 8$, $N_R = 10$, and $N_L = 8$ antenna configurations. In these two examples $2N_L > N_R$, which means that our algorithm starts selecting receive antennas with full set and removes one antenna per step to

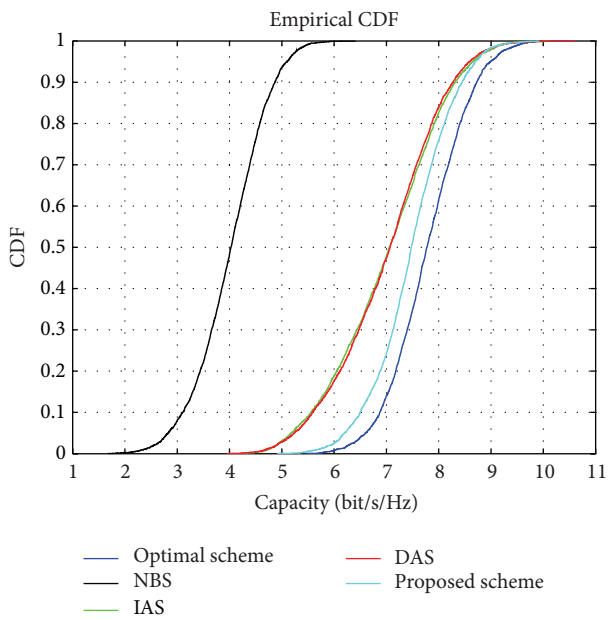

Figure 2: CDF curves of system capacity with $N_L = 2$ (SNR = 6 dB).

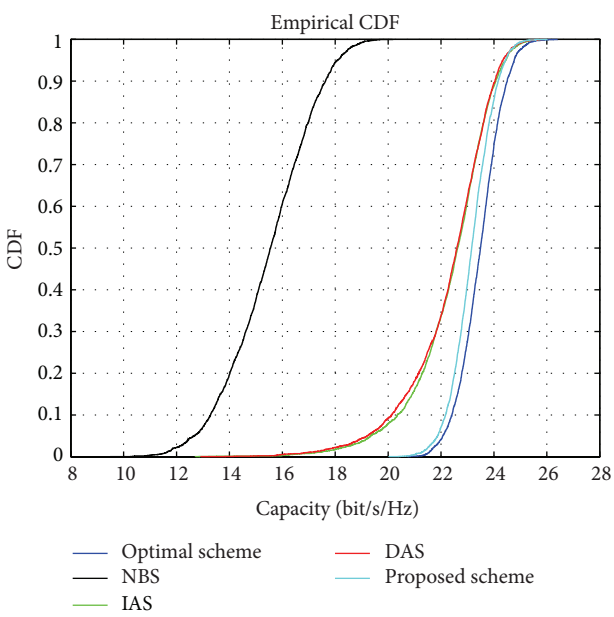

Figure 3: CDF curves of system capacity with $N_L = 2$ (SNR = 30 dB).

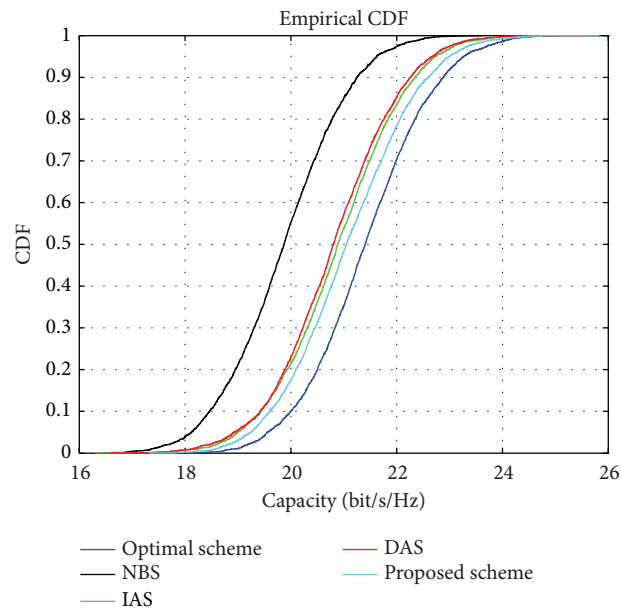

Figure 4: CDF curves of system capacity with $N_L = 8$ (SNR = 6 dB).

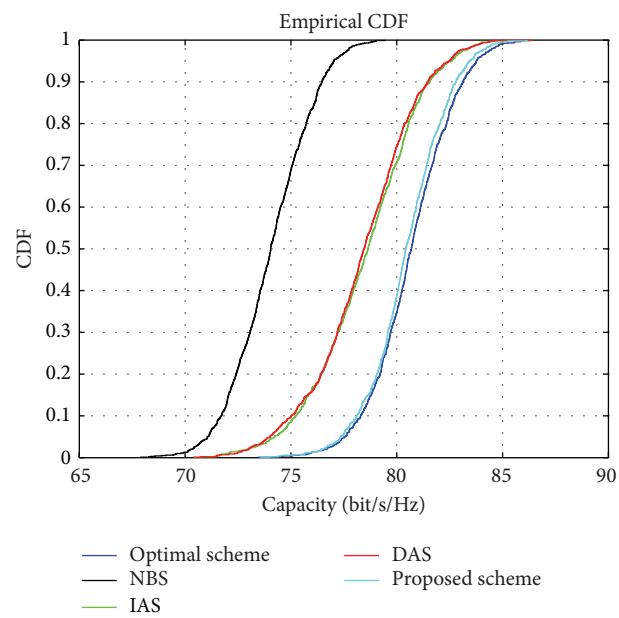

Figure 5: CDF curves of system capacity with $N_L = 8$ (SNR = 30 dB).

obtain the final subset. While IAS needs eight steps to get it, the proposed algorithm still only needs two steps. It is shown that no matter how many receive antennas are selected, our algorithm takes the lowest steps to obtain the set of selected antennas. In realistic system, our scheme is more convenient and costs less time to choose the suboptimal subset of antenna through its adaptive feature based on the configuration of real scenario while remain considerable system performance compared with the optimal one.

Figures 6 and 7 show the comparison results of five algorithms, and the range of SNR is 0 dB to 30 dB. In order to get these curves, in these two figures at each point of SNR, we use the mean value of 5000 times simulation results. From these two figures we can see that IAS and DAS have almost the same system performance while our proposed scheme is better than them and yields a negligible loss in system capacity as compared to the optimal selection. The reason is that IAS and DAS use the same system model to get their antenna selection criterion while in our proposed scheme we

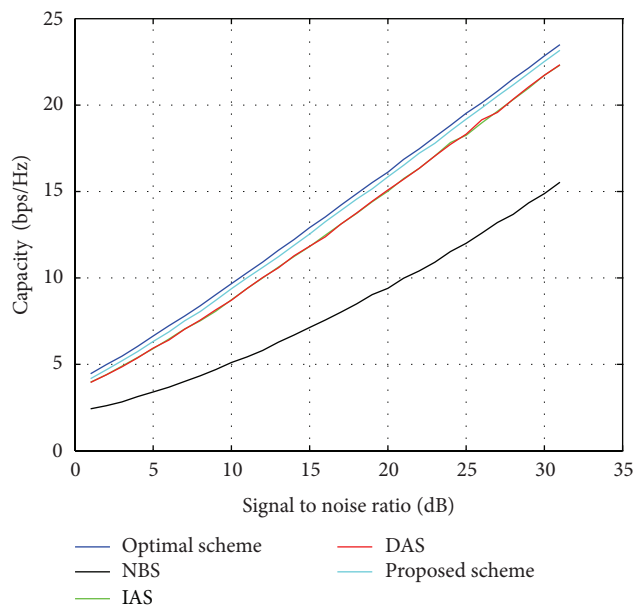

Figure 6: Comparison results of different algorithms with $N_L = 2$, $N_R = 10$.

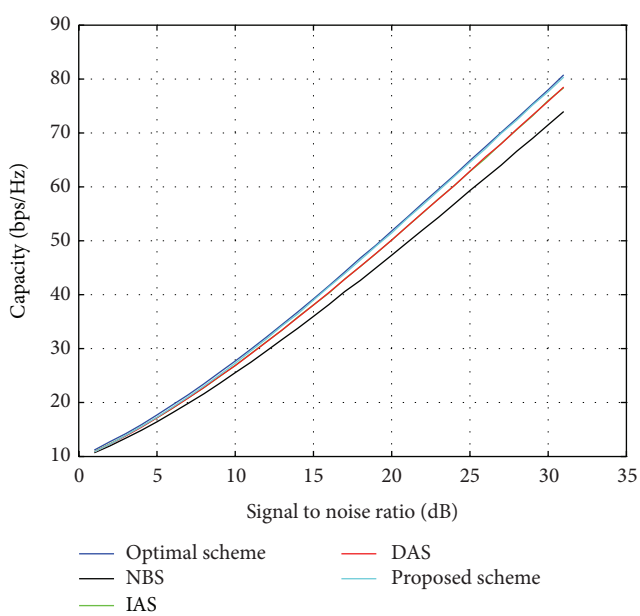

Figure 7: Comparison results of different algorithms with $N_L = 8$, $N_R = 10$.

improve the system model and based on it we obtain our novel antenna selection criterion which is much approximate to realistic system in moderate and high SNR region.

5. Conclusions

A fast adaptive iteration antenna selection algorithm for MIMO systems has been proposed in this paper. Our method can choose antenna selection strategy based on the proportion of N_L and N_R in real systems to make sure that it can obtain the set of selected antennas through the least steps. From simulation results we can see that our algorithm gets better system performance in MIMO systems than IAS and DAS, and it reduces computational cost significantly compared with the optimal one. So it is an effective method to acquire the diversity benefits of multiple antennas.

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