# The complexity analysis and performance comparison of MIMO systems based on antenna selection techniques

**Yisong Lin[1], Mingjie Zhuang[2]***

[1]*School of Information Science and Engineering, Huaqiao University, Xiamen 361021, China*

[2]*College of engineering, MJZhuang176@163.com, Huaqiao University, Quanzhou, 362021, China*

*Received 1 March 2014, www.cmnt.lv*

**Abstract**

MIMO systems, also known as multiple-input multiple-output, can effectively improve the capacity and reliability of wireless communication. Antenna selection (AS) is a low-cost low-complexity attractive approach in MIMO systems that capture many advantages of these systems. In this paper, we comprehensively review and describe various kinds of AS schemes in MIMO systems. First, we discuss the techniques of antenna selection from the perspective of different channel environments. Analysis results show that exploiting the AS technique can avoid sending redundant information and improve the channel capacity in the low rank and correlated channel conditions. Then the applications of AS systems in spatial diversity and spatial multiplexing are considered. In order to reduce the complexity of AS algorithm, we propose a novel joint transmit and receive AS scheme in MIMO systems. The results of simulations demonstrate that the proposed AS method of performance outperforms other methods, and the proposed algorithm can significantly reduce computational complexity compared to the optimum algorithm. Finally, we summarize some conclusions about the antenna selection.

*Keywords:* MIMO, antenna selection, spatial diversity, spatial multiplexing

## 1 Introduction

Using multiple input, multiple output (MIMO) systems is one of the most significant technical breakthroughs in modern wireless digital communications. Compared with single inputs single output (SISO) systems, the capacity and reliability of a wireless communication system can be improved dramatically by employing multiple antennas at the transmitter and/or receiver without increasing bandwidth and transmit power [1]. MIMO technology has been drawn significant research interests recently due to its advantages. Most importantly, the standard for the third-generation cellular phones (3rd generation partnership project, 3GPP) has joined the MIMO technology. The MIMO technology has been widely applied to Beyond 3G and 4G systems. We can foresee that the mobile communication systems in the future, including the 5G system, will be implemented by massive MIMO technology [2].

It is shown that in an independent and identically distributed (i.i.d.) Rayleigh fading channel, the capacity of a MIMO system with $N_T$ transmit antennas and $N_R$ receive antennas scales almost linearly with the $min(N_T, N_R)$ in the high signal-to-noise ratio (SNR) regime [1]. The MIMO wireless communication systems have now demonstrated the potential for increased capacity and reliability in rich multipath environments, without any increase in bandwidth or transmit power. However, the application of multiple antennas has been restricted by the hardware cost and power consumption of the RF chains. Because it requires the same number of RF chains at the transmitter and receiver. The RF chains include amplifiers, up-down converters, as well as the analog-to-digital-to-analog (A/D/A) conversions. The cost and hardware complexity of the RF chains is often much higher than the antenna array. How to reduce the hardware complexity and at the same time maintain most of the advantages of MIMO systems is an important research topic. A MIMO system with antenna selection (AS) has been shown to significantly outperform a system exploiting the same number of RF chains without AS. Therefore, the AS approach that chooses a subset of the available transmit and/or receive antennas is an attractive low-cost and low-complexity technique. The MIMO technology improves the wireless communication system performance from two aspects, spatial multiplexing and spatial diversity. First, from the point of view of spatial diversity, MIMO systems can improve the signal-to-noise ratio (SNR) and the robustness of the communication links in terms of BER (Bit Error Rate) by collecting multipath signals between the transmitter and receiver. On the other hand, spatial multiplexing, which makes full use of independent space degrees of freedom between the transmitter and receiver can dramatically improve the capacity and the speed of data transmission of the communication system.

The remaining sections of this paper are organized as follows. We will introduce MIMO systems with AS techniques and discuss AS schemes in various kinds of operation environments of actual channel in Section II. AS systems based on both spatial diversity discussed and analysed In Section III. Section IV studies mainly the AS criterions based on spatial multiplexing, and analyses the complexity of various kinds algorithms. Section V describes the simulative results and discussion. Finally, the prospection and conclusions are included in Section VI.

***Corresponding author** e-mail: MJZhuang176@163.com

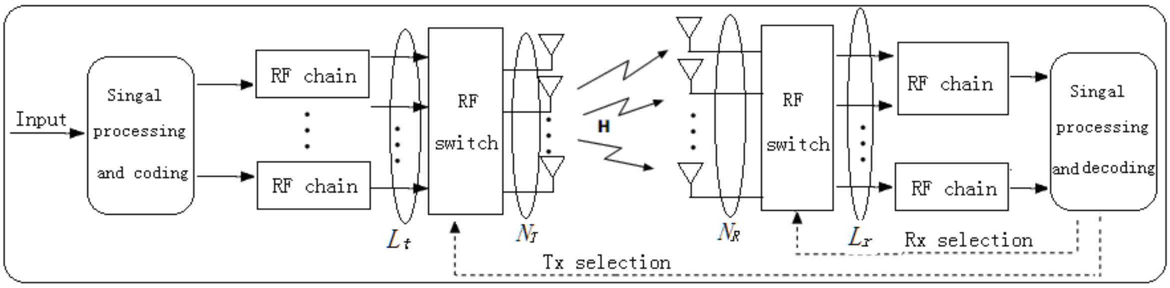


FIGURE 1 Antenna selection in MIMO system

## 2 Antennas selection of channel model

### 2.1 MIMO SYSTEM CHANNEL MODEL

Figure 1 shows the MIMO systems with $N_T$ transmit antennas and $N_R$ receives antennas. The transmitter includes an STBC encoder, RF chains, and a switch that connects the RF chains to select $L_t$ out of $N_T$ transmit antennas according to the message of *Tx* selection through feedback channel from the receiver. Likewise, at the receiver, a switch connects the RF chains to select $L_r$ out of $N_r$ receive antennas according to the message of Rx selection from the signal processing unit, in which during a period of the received signals process the channel state information (CSI) of MIMO systems is estimated. Assuming all $N_T$ transmit antennas and $N_R$ receive antennas are selected, the complex envelope of the received signal at the antenna array after matched filtering is given by:

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

where $x$ is a $N_T$ dimensional column vector of the transmitted signals, and $n$ is a $N_R$ dimensional complex noise vector where each component is a complex white Gaussian noise sample with zero mean and variance $\sigma_n^2$. The channel matrix is defined in Equation (2)

$$H=\begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_T} \\ h_{21} & h_{22} & \cdots & h_{2N_T} \\ \vdots & \vdots & \vdots & \vdots \\ h_{N_R1} & h_{N_R2} & \cdots & h_{N_RN_T} \end{pmatrix}, \tag{2}$$

where matrix $H$ is a $N_R \times N_T$. It is assumed that the matrix $H$ is independent complex Gaussian random variables with zero mean and unit variance, namely, all of the transmitted signals experience frequency selective flat Rayleigh fading channel. The element $h_{ij}$, $i$=1,2,…$N_R$; $j$=1,2,…$N_T$, of the matrix $H$ represents the complex channel gain between the $j$-th transmit antenna and the $i$-th receive antenna.

### 2.2 THE EFFECT OF CHANNEL SITUATIONS ON AS

The capacity of wireless communication system has been severely influenced by the channel situations [3]. A lot of AS schemes on MIMO systems have been discussed in the different channel conditions [4-11]. Under the flat Rayleigh fading channels, assuming that MIMO wireless channels are mutually independent, the references [4-8] presented some AS schemes. These results indicated that AS technique can capture most of the advantages of MIMO systems and at the same time reduce the hardware complexity. If the wireless channels are independent, we can be sure that the performance of the system will be deteriorated in the correlated channels. The fact that the channel is correlated implies that some rows/columns in the channel matrix can be expressed as a linear combination of the others. This means that the information in these rows/columns is in some way redundant and does not contribute to capacity. It is thus clear that redundant information is easily produced in the correlated channel situation. To do this, a fast AS algorithm based on Frobenius norm and correlation coefficient was proposed in [7]. This algorithm chooses two rows of the channel matrix, which carry identical information, since they own similar signal components, one of them will be deleted in this scheme. In addition, the two rows have different powers, or rather squared Frobenius norm of the row, the correspondding row with higher power will be selected in the algorithm. When there are no two rows of identical information, the algorithm in [9] choose two rows of the channel matrix, which have higher correlation factor, and the corresponding row with lower power will be deleted. In a word, it allows us to obtain a sub-channel matrix whose rows are minimally correlated and have maximum powers. Further, in a low rank and correlation matrix channel, it is easy to send redundant information, which does not contribute to the channel capacity. It is necessary to select a set of antenna in a low rank channel conditions, so that the total transmission power may be allocated to a small amount of transmit antennas to improve the capacity of the system. An optimal AS algorithm in the low rank matrix channel was proposed in [10]. It has shown that AS in the low rank matrix channel can still improve the capacity of the channel. And in the seriously frequency selective fading channel, it has been shown that the effect on AS is very little. However, when the bandwidth of the system is greater than the correlated bandwidth of channel, an additional degree of diversity which is generated by AS is not prominent. Even so, the advantages of antenna selection are still reflected in a general frequency selective fading channels. According to reports in the [11], it shows that CDMA signals, in a general frequency selective channels, can be exploited to maximize the SNR at the receiver based on both generalized combined, in which combined multiple copy signals, and pre-coding technique as well, at the same time it can reduce the complexity of the transmitter and receiver.

## 3 AS systems based on spatial diversity

MIMO technique can greatly improve the performance of the wireless communication systems by exploiting the independence of the channel space. Namely, it takes advantage of the degrees of freedom provided by multiple antennas and the technique of time/spatial diversity to improve the performance and reliability of wireless communication. Diversity refers to two or more random fading signals are merged to reduce the fluctuation of signal level. As Figure 2 shows a block diagram of conventional receive diversity. All of the transmit signals experience a different fading channel with complex valued coefficient $h_i(t)$ and additional noise signal $n_i(t)$. Due to multiple fading paths are statistically independent, it is unlikely that they appear synchronous fading phenomenon. At any moment, the probability of all uncorrelated fading signals simultaneously in a deep fading is small. Therefore, diversity can significantly reduce fading degree of the combined signals. At present, diversity has been widely exploited in wireless communication systems to against the multipath fading.

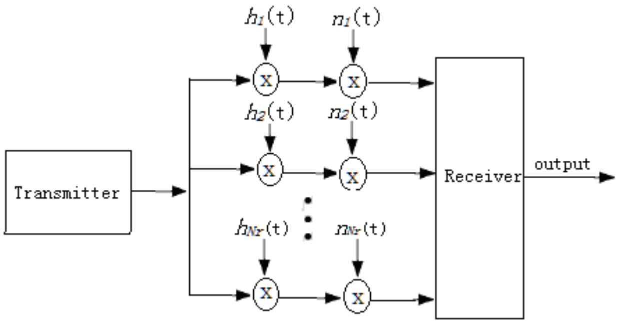


FIGURE 2 Block diagram of receive diversity

### 3.1 THE TRADITIONAL DIVERSITY

Figure 3 shows a generalized receive antenna selection diversity system, which is an extension of the conventional receive diversity. The independent signals after the antenna selection must be combined at the receiver to improve the signal-to-noise ratio (SNR) of the system. Diversity combining can be classified into three categories by the different ways of signals combination. They are maximal ratio combining (MRC), equal gain combining (EGC) and selection combining (SC). Although the implement of MRC would be relatively complicated, it is still an optimal technique of diversity combining which gives a better performance of the system. With the development of semiconductor and signal processing techniques, MRC technique now has been widely exploited in communication systems. A rapid incremental AS approach, in which at each step a new antenna is added to the selected antenna subset based on the maximum output SNR strategy, for MIMO diversity systems using maximum ratio transmit (MRT) at the transmitter and MRC at the receiver was proposed by Duan Hong, and Liu Feng in [12]. It shows that the MIMO AS systems can keep most of the diversity gain, and do not need too many RF chains. In addition, the performance analysis of a kind of reduced-complexity transmit/receive diversity systems and SNR and bit error rate (BER) of hybrid SC/MRC systems are discussed respectively in [13, 14], study results show that it shows that the system performance is obviously improved.

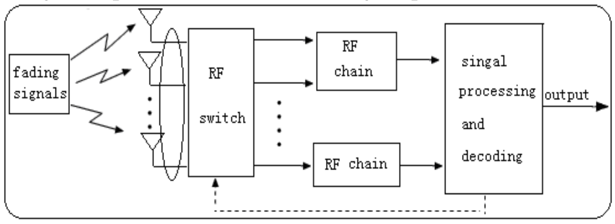


FIGURE 3 Block diagram of generalized receive AS diversity system

### 3.2 THE SPACE-TIME DIVERSITY

As mentioned above, through hybrid the AS technology and traditional MIMO diversity, we can greatly boost the diversity gain, thus output SNR and BER performance of the communication systems are obviously increased and improved. However, in the actual operating environments, it may bring the mutual interference of transmitting antennas by exploiting the multi-antenna. In order to reduce mutual interference of transmitting antennas, an optimal AS with space-time block coding was proposed in [15]. Research shows that MIMO AS systems with the space-time coding can obtain certain additional diversity advantages. The input serial data from signal constellation are performed series-to-parallel to multiplex parallel data streams, and then the processed data employing space-time coding are transmitted in sequence over the selected antennas. So transmit diversity advantage will be produced by space-time two dimensional coding in the transmitter. It shows that transmit antenna selection with space-time block coding (STBC) can greatly improve the performance of BER in communication systems [16]. At the same time, [17] shows that antenna selection combined with quasi-orthogonal STBC can improve the diversity gain and coding gain to reduce BER. The investigation results in [18] indicate that quasi-orthogonal STBC systems with AS can increase the capacity of the channel and improve the transmission rate of the system. [19] points out that the diversity gain and closed loop gain of the system can improved greatly by combining V-BLAST and antenna selection algorithm.

Finally, we can conclude that MIMO systems combining with space-time code will be a key technology in the future high-speed transmission communications. Employing MIMO AS systems not only can reduce tremendously the system implementation complexity and cost, but also provide a higher diversity gain and enhance the SNR magnitude. The following section, we will verify MIMO AS systems can increase effectively the channel capacity and improve the rate of transmission as well.

## 4 AS systems based on spatial multiplexing

As we known, MIMO can greatly improve the channel capacity and the rate of data transmission of the system by exploiting spatial multiplexing. With the increase of number of transmit and receive antennas, the channel capacity of

MIMO systems will increase linearly. As shown in the Figure 1, the MIMO system equips with $N_T$ transmit antennas and $N_R$ received antennas. Assume that the MIMO wireless channel is modelled as a Rayleigh fading distribution. Based on spatial multiplexing, the AS criteria of MIMO system is to select an antenna subset, in which subset can achieve the maximum channel capacity. On the basis of the channel matrix $H$, $L_t$ out of $N_T$ transmit antennas and $L_r$ out of $N_R$ receive antennas are selected from MIMO system, let the selected sub-matrix be denoted by $\tilde{H}$ . Assuming that the system transmission power is evenly allocated to each of the transmitting antennas, thus the channel capacity of MIMO system can be expressed as [1]:

$$C_{\text{full}} = \log_2[\det(I_{N_T} + \frac{\rho}{N_T} H^H H)], \qquad (3)$$

where $\rho$ denotes the average signal-to-noise ratio (SNR), $H$ is the $N_R \times N_T$ channel matrix. $I_N$ denotes a $N \times N$ identity matrix. The superscript H denotes the conjugate transpose.

The channel capacity of sub-matrix $\tilde{H}$ corresponding to the optimal antenna subset can be written as:

$$C_{\text{sel}} = \max_{S(\tilde{H})}\{\ \log_2[\det(I_{N_T} + \frac{\rho}{N_T} \tilde{H}^H \tilde{H})]\}\ . \qquad (4)$$

However, the computational load required for an optimal selection through an exhaustive search over all possible antenna subsets grows exponentially with the total number of the antennas available. This is a computationally prohibittive problem. High-speed communications systems demand an efficient AS scheme with lower complexity, so the investigation of the sub-optimal AS algorithms is of great practical as well as theoretical interest.

## 4.1 RECEIVE ANTENNAS SELECTION

The Receive antennas selection (RAS) system based on spatial multiplexing is choosing the channel matrix to maximize the channel capacity in the receiver. The simplest RAS algorithm is norm-based selection (NBS), which was proposed in [4]. Selection criteria of NBS is that the row of channel matrix with the maximal Frobenius norm is chosen in each step selection algorithm. Due to lower computational complexity, NBS is the most suitable for low SNR or only a RF link at the receiver. However, NBS is not necessarily optimal in other scenarios. The lower complexity of NBS, the more losses of channel capacity, in order to reduce the losses of channel capacity, a fast antenna selection is proposed in [5]. The algorithm begins with the full channel matrix, and then removes one antenna per step. So the AS criteria is based on the antenna with the lowest contribution to the system capacity is removed per step. In contrast to [5], an incremental antenna selection algorithm is proposed [6,7]. The computational complexity is much lower than the algorithm of [5]. The algorithm starts with an empty antenna subset and adds one antenna per step to this subset. At each step, the objective is to select one antenna, which leads to the highest contribution to the channel capacity. Although the computational complexity of the algorithm [6, 7] will be lower than AS algorithm [5], there are still some losses of channel capacity. These algorithms [5-7] can substantially reduce the computational load in the AS systems, however, they are still restricted by so called local searching shortcomings. These local searching strategy, though reduce the computational load, give rise to the loss in optimality simultaneously. A kind of global and fast receiver antenna selection for MIMO systems was proposed [8], it takes into account the number of RF chains is the same both at the transmitter and receiver. It allows to finding the sub-matrix with the greatest determinant for a high SNR scenario. It shows that the fast AS algorithm can achieve almost the same capacity performance as the optimal selection method.

In order to illustrate the performance of the antenna selection, the channel capacities of different algorithms are simulated with 1000 random number seed by Monte Carlo method. Figure 4 shows that comparison of the channel capacity the incremental algorithm [6, 7], decreasing algorithm [5], global and fast antenna selection method [8] for $L_r = N_T = 3$, $N_R = 6$, and the value range of SNR is $0dB$ to $20dB$. It can be seen that, obtain almost the same capacity performance as the optimal selection method. While the NBS [4] has a certain losses of channel capacity compared to the optimal algorithm. Table 1 shows the complexity of antenna selection algorithms. It shows that the complexity of NBS selection algorithm is smallest. While the complexity of global and fast antenna selection method [8], the incremental algorithm [6, 7] are smaller than decreasing algorithm [5].

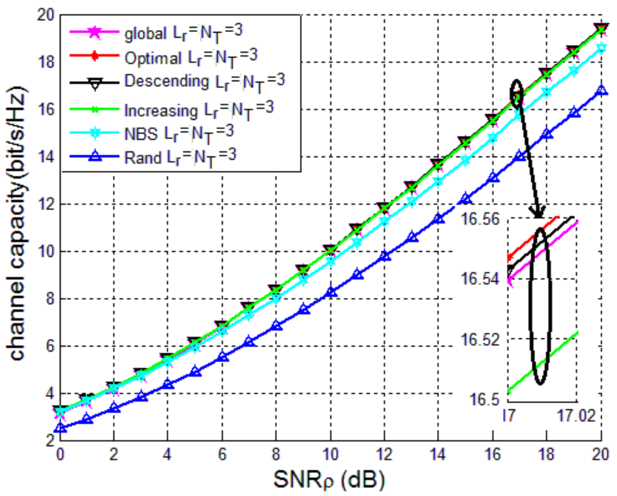


FIGURE 4 The channel capacity versus SNR

TABLE 1 Comparison of computational complexity for AS algorithms

| Descending [5] | Increasing [6] | Global [8] | NBS [4] |
|---|---|---|---|
| $N_R^2 N_T^2$ | $max\{N_T, N_R\} N_T L_r$ | $N_R N_T^2$ | $N_R N_T$ |

## 4.2 TRANSMIT ANTENNAS SELECTION

In the same way, transmit antenna selection (TAS) performs to select the optimal transmit antenna subset at the MIMO transmitter employing full or partial channel state information (CSI). However, TAS implementation is more difficult than RAS. This is because TAS MIMO systems need a dedicated feedback channel to feed the CSI from the channel estimator unit at the MIMO receiver. In order to ensure performance of TAS system, known perfect CSI at the transmitter is very important. In practical scenario, the wireless channel is random variation, achieving perfect CSI is very complicated. Therefore, it is inevitable to receive a small fraction of the error CSI. Effect of imperfect CSI on the channel capacity of the MIMO systems with TAS is obvious. Like the RAS systems, compared to without TAS, the capacity performance of MIMO systems with TAS will be greatly improved [20].

### 4.3 JOINT TRANSMIT AND RECEIVE ANTENNA SELECTION

Figure 1 shows the MIMO system equips with $N_T$ transmit antennas and $N_R$ received antennas. There are $L_t$ and $L_r$ RF chains at the receiver and transmitter, respectively. Assuming all $N_T$ transmit antennas and $N_R$ receives antennas are selected. The object is to select the best $L_r$ out of $N_R$ antennas at the receive side and the best $L_t$ out of $N_T$ antennas at the transmit side so that the resulting system capacity is maximized. The channel matrix H is an $N_R \times N_T$ complex valued matrix. The ideal antenna selection technique chooses $\tilde{H}$ (is an $L_r \times L_t$) out of H. The optimal subset selection which can always be obtained by fully searching overall the possible row and column combinations of the channel matrix $H$. The performance of systems that using the optimal subset selection has much higher than that of the systems using the same number of antennas without any selection. However, the complexity of the optimal algorithm is $C_{N_R}^{Lr} \cdot C_{N_T}^{Lt}$, which may not be feasible. The joint transmit and receive antenna selection algorithm [21] was first proposed to decouple the joint antenna selection problem into separate transmit and receive antenna selection and carried out the exhaustive search. So the algorithm requires computing $C_{N_R}^{Lr} + C_{N_T}^{Lt}$ determinants of size $L_r \times L_t$ sub-matrices for the exhaustive search. In order to select the appropriate subset of antennas, antenna subset selection problems have been intensively studied in the [22-29], a similar decoupling strategy has also been used in the separable transmit/receive successive selection [22]. The selection algorithm adopted the fast incremental successive selection algorithm [7] for both transmit and receive side selection in the decoupled problem. The complexity of this algorithm is $max\{N_T, N_R\}^2 L^2$. It results in the huge complexity reduction compared to the algorithm [21]. But, it has a loss of performance compared to the optimal selection.

Although the decoupling-based strategies can reduce the computational burden of the problem of joint transmit and receive antenna selection, the complexity of this decoupling-based strategies is still large. To reduce the computational complexity, the successive joint transmit and receive antenna selection algorithm is proposed in [23-26]. The algorithms start with the empty set of selected antennas and add one pair of antenna per step to this set. At each step, the objective is to select one pair of antenna, which leads to the highest contribution to the system capacity. The joint transmit and receive selection strategies by exploiting stochastic optimization algorithms such as the genetic algorithm [27, 28] or particle swarm optimization [29] have also been investigated to find the subset of the antenna to achieve maximum instantaneous channel capacity. It is assumed that $N_T = N_R = N$. Then, the complexity of CJAS [25] is $N^2L^3/2$. It is large when the number of the selected antennas is more than $N/2$. A novel joint transmit and receive antenna selection algorithms is proposed. It is calculating the capacity reduce instead of the whole subsystem capacity when selecting a new candidate pair of antenna at each step. In each step, our objective is to select one pair of antenna, which leads to the lowest contribution of the capacity. The complexity of the proposed algorithm is $3\times N^4/4 - 3\times (N-L)^4/4$. Table 2 shows the complexity of three antenna selection algorithms, we can find that the computational complexity of the proposed antenna selection algorithm is far less than the optimal antenna selection algorithm. When the number of selected antennas is more than $N/2$, the complexity of the proposed algorithm is less than CJAS [25]. So it is suitable for more number of selected antennas.

TABLE 2 The complexity comparison for transmit and receive antenna selection algorithms

| algorithm | complexity | *N*=8, *L*=2 | *N*=8, *L*=3 | *N*=8, *L*=4 | *N*=8, *L*=5 | *N*=8, *L*=6 |
|---|---|---|---|---|---|---|
| optimal algorithm | $C_N^L C_N^L L^3$ | 6272 | 84672 | 313600 | 392000 | 169344 |
| proposed algorithm | $\frac{3}{4}N^4 - \frac{3}{4}(N-L)^4$ | 2100 | 2603 | 2880 | 3011 | 3060 |
| CJAS | $N^2L^3/2$ | 256 | 864 | 2048 | 4000 | 6912 |

## 5 Results and discussion

In this section, we consider the MIMO AS systems channel model as mentioned before, the elements of $H$ are represented by independent complex Gaussian random variables with zero mean and unit variance. The simulation results will be vastly presented to compare the proposed algorithm with other joint transmit/receive AS algorithms, such as optimum selection (OS), NBS, and CJAS [25]. In order to illustrate more clearly the performance of the proposed algorithms and other AS approaches, we will plot a large number of graphs to describe the channel capacity and the cumulative distribution function (CDF), they are the curves of channel capacity as a function of SNR and different selected antenna numbers, and CDF as a function of channel capacity and SNR. These curves are plotted by computer Monte

Carlo simulation using a certain random number data (e.g., 1000, or 2000).

Figure 5 shows the comparison results of five algorithms with $L_r$=$L_t$ =2, $N_T$=$N_R$=5, and the value range of SNR is 0*dB* to 20*dB*. In order to get these curves, in the two figures at each value of SNR, we average statistically to 1000 simulating values. It can be observed that the performance of our proposed algorithm is better than CJAS [25]. The figure also indicates that the proposed algorithm has almost the same performance with optimum AS. The reason is that our proposed algorithm removes the antenna serial number, which leads to the smallest contribution of channel capacity and yields a negligible lossed to channel capacity, compared to the optimal selection. Figures 5 and 6 show that the more number of selected antennas at the transmitter and receiver, the greater channel capacity of MIMO systems. This is because MIMO wireless systems have the potential for increased capacity in rich multipath environments.

Figures 7 and 8 show the CDF curves as a function of system channel capacity for the case of SNR = 8*dB* and 20*dB* with $L_r$=$L_t$=3, $N_T$=$N_R$=7. It can be observed that our algorithm also obtains closer curve to the optimal one with higher SNR. From the simulation results we can observe that our proposed algorithm perform better performance of channel capacity than CJAS [25], in addition, it can reduce computational cost significantly compared with OS scheme. So our proposed algorithm is an effective method, at the same time, it has multiple antenna diversity advantage.

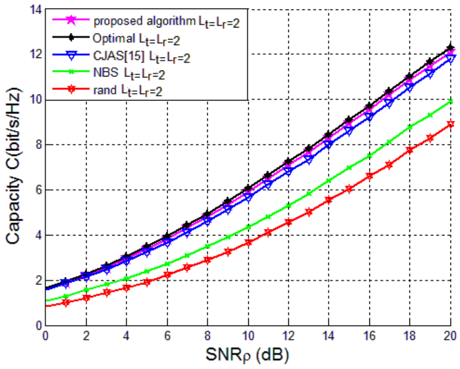


FIGURE 5 channel capacity versus *SNR* with $L_r$=$L_t$ =2, $N_T$=$N_R$=5

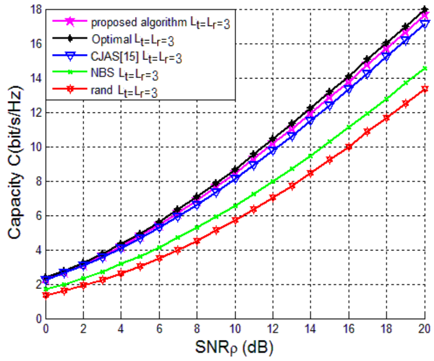


FIGURE 6 channel capacity versus *SNR* with $L_r$=$L_t$ =3, $N_T$=$N_R$=7

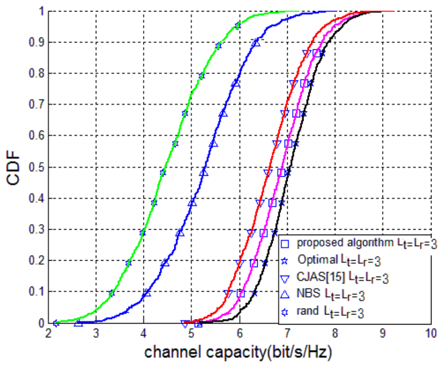


FIGURE 7 the CDF curves versus channel capacity with $L_r$=$L_t$=3, $N_T$=$N_R$=7 (*SNR*=8*dB*)

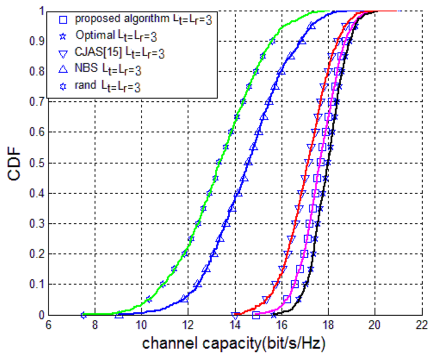


FIGURE 8 the CDF curves versus channel capacity with $L_r$=$L_t$=3, $N_T$=$N_R$=7 (*SNR*=8*dB)*

## 6 Conclusions

This paper presents an overview of antenna selection in MIMO systems. It focused on the spatial diversity and spatial multiplexing system. It shows that AS can reduce system implementation complexity and hardware cost, and achieve full diversity gain, and enhance the channel capacity and transfer rates. A novel joint transmit and receive antenna selection algorithm is presented in this paper. Our proposed algorithm is suitable for more number of selected antennas. Computer simulations show that the proposed algorithm can achieve near optimal channel capacity performance, while the overall complexity of the proposed algorithm is signifycantly lower than that of the optimal exhaustive search. However, there are still several problems in antenna selection, such as the problem of sub-optimal joint transmit and receive AS algorithm is still worth researching. How to evaluate performance of AS algorithms when there is a delay of feedback channel state information. At present, antenna subset selection problems have been intensively studied in Rayleigh fading channels, and Nakagami fading channels still needs more research.

## Acknowledgments

The authors would like to thank the anonymous reviewers of this paper for their carefully reading of the manuscript as well as their many constructive comments. This paper is supported by the Technology Research and Development Projects of Quanzhou city (2012Z82), the Natural Science Foundation of Fujian Province of China (No. 2012J01270), and the Natural Science Foundation of Huaqiao University (Excellent Level Talents) (No.11BS430).

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## Authors


**Yisong Lin, born in 1989, Anxi, Fujian province, China**

**Current positon, grades**: Graduate student in the Hua Qiao University, China.
**University study:** Bachelor degree of Information Engineering Henna Institute of Science and Technology in 2012.
**Research activities:** wireless communications.

**Mingjie Zhuang, born in 1964, Hui'an, Fujian province, China**

**Current positon, grades** professor in Huaqiao University, China.
**University study:** Fudan University (Department of Electronic Engineering), Shanghai, 1982,Ph.D. degree in information and communications engineering, Xiamen University, Xiamen, Fujian, 2001.
**Research activities**: wireless communication technology, space-time processing, and stochastic processes.