Notification from Editors

“Iterative Transmit/Receive Antenna Selection in MIMO Systems Based on Channel Capacity Analysis” by Peng LAN, Ju LIU, Fenggang SUN and Peng XUE, IEICE Transactions on Communications, vol.E94-B, no.3, pp.844-847, March 2011.

This manuscript was canceled on August 6, 2013 because it was found to be a duplicate submission.

LETTER

Iterative Transmit/Receive Antenna Selection in MIMO Systems Based on Channel Capacity Analysis**

Peng LAN^{†*a)}, Ju LIU^{††}, Fenggang SUN[†], Nonmembers, and Peng XUE^{†††}, Student Member

Peng LAN, Ju LIU, Fenggang SUN and Peng XUE,

"Joint transmit and receive antenna selection in mimo systems for maximize channel capacity,"

Journal on Communications, vol.30, no.7, pp.7-12, July, 2009.

key words: MIMO, antenna selection, channel capacity, outage capacity

1. Introduction

The need to greatly increase the channel capacity has motivated recent interest in multiple-input multiple-output (MIMO) systems [1], [2]. In practice, however, the cost corresponding to the RF chains for the multiple antennas and the high complexity required for signal processing makes the implementation of MIMO system intractable. Cost-effective approach to solve these problems is antenna selection [3], [4], where only a subset of transmit and receive antennas is employed.

With the aim of choosing the appropriate antenna subset, the antenna subset selection algorithms in MIMO systems have been intensively studied in a variety of publications [4]–[10]. The optimal selection algorithm is an exhaustive search of all possible combinations of the antennas [4]. However, the computational complexity required for such optimal selection algorithm polynomial grows with the product of the number of transmit and receive antennas, which makes this method computationally prohibitive. Therefore, a series of simplified antenna subset selection algorithms that aim to reduce the computational complexity have been proposed. The simplest antenna selection algorithm known until now is the norm-based selection (NBS) algorithm [5]. In [6], the NBS algorithm was used in the

MIMO system for joint transmit and receive antenna selection, the simulation results show that when the number of antennas is small, this method can achieve almost the same performance as the optimal. Based on the analysis of channel capacity maximization, the receive antenna selection (RAS) algorithms proposed in [7], [8] can achieve near the optimal performance. Further in [9], [10], the idea of RAS algorithms was extended to the system with transmit and receive antenna selection. We refer to these algorithms as decoupled transmit and receive antenna selection (DTRAS) because they need to find the same performance as MIMO space multiplexing systems.

In this letter, we propose a new optimal iterative transmit/receive antenna selection algorithm. Different from DTRAS algorithms, the new algorithm selects transmit and receive antennas simultaneously. Although the algorithm adds some computational complexity, the simulation results demonstrate that the proposed selection algorithm almost matches the capacity of the optimal selection method.

2. System Model

Consider a MIMO system, in which the transmitter has N_T antennas and $n_T (\leq N_T)$ RF chains, and the receiver has N_R antennas and $n_R (\leq N_R)$ RF chains. The channel is frequency-flat Rayleigh fading with additive white Gaussian noise (AWGN). The input-output relationship for a MIMO system with N_T transmit antennas and N_R receive antennas is given by

$$\mathbf{r} = \sqrt{\frac{\rho}{N_T}} \mathbf{H} \mathbf{x} + \mathbf{w}, \quad (1)$$

where $\mathbf{r}$ is an $N_R \times 1$ received signal vector, $\mathbf{x}$ is an $N_T \times 1$ transmitted signal vector, $\mathbf{w}$ is zero mean additive noise with unit energy, ρ is the average signal-to-noise ratio (SNR) at each receive antenna, and channel matrix $\mathbf{H}$ with size $N_R \times N_T$ can be denoted as

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1} & h_{N_R,2} & \cdots & h_{N_R,N_T} \end{bmatrix} \quad (2)$$

in which $h_{i,j} (1 \leq i \leq N_R, 1 \leq j \leq N_T)$ is a zero-mean circularly symmetric complex Gaussian random variable with unit variance.

Manuscript received July 29, 2010.

Manuscript revised November 8, 2010.

[†]The authors are with the School of Information Science and Engineering, Shandong Agricultural University, China.

^{††}The author is with the School of Information Science and Engineering, Shandong University, China.

^{†††}The author is with Samsung Advanced Institute of Technology (SAIT), Korea.

*Corresponding author.

**This work was supported by Shandong Agricultural University, China and The Cultivation Fund of the Key Scientific and Technical Innovation Project, Ministry of Education of China (Grant No.708059).

a) E-mail: lanpeng@sdau.edu.cn

DOI: 10.1587/transcom.E94.B.844

3. Iterative Transmit/Receive Antenna Selection

We study the problem of $n_T = n_R = n_m$ MIMO systems. For the case of $n_T < n_R$, we can first allot the $n_R - n_T$ receive RF chains using the algorithms in [7], [8] and then using the proposed algorithm to select the left n_T pairs of transmit and receive antennas.

Assuming that after transmit and receive antenna selection, the channel matrix that corresponds to the n_m pairs of selected transmit and receive antennas is $\hat{\mathbf{H}}$ and the capacity of the system can be expressed as

$$C(\hat{\mathbf{H}}) = \log_2 \left[\det \left(\mathbf{I}_{n_m} + \frac{\rho}{n_m} \hat{\mathbf{H}} \hat{\mathbf{H}}^H \right) \right]. \quad (3)$$

Therefore, the aim is to find the optimal n_m pairs of transmit/receive antennas, i.e. the optimal channel matrix $\hat{\mathbf{H}}$, to maximize the channel capacity.

To avoid exhaustive search, we propose a low complexity algorithm. There are total n_m steps, and in each step we select one pair of transmit and receive antennas which provides the maximum capacity increase.

3.1 Capacity Analysis with One More Antenna Pair

Assume that in the n th step, the $n \times n$ matrix $\mathbf{H}_n$ corresponds to the channel matrix of the selected n pairs of transmit and receive antennas. Denote $\mathbf{T}$ and $\mathbf{R}$ as the index sets of the selected transmit and receive antennas, $\mathbf{S}_T$ and $\mathbf{S}_R$ as the index sets of transmit and receive antennas that are still not selected.

We first analyze the channel capacity. If transmit antenna Q and receive antenna P are selected in the $(n+1)$ th step. The $n \times 1$ vector $\mathbf{g}_{R,Q}$ denotes the channel between the transmit antenna Q and the receive antennas that belong to $\mathbf{R}$. Defining $\mathbf{r} = \mathbf{T} \cup Q$, the $(n+1) \times 1$ vector $\mathbf{h}_{P,\mathbf{r}}$ denotes the channel between the receive antenna P and transmit antennas belonging to $\tilde{\mathbf{T}}$. The channel matrix becomes $\tilde{\mathbf{H}}_n = [\mathbf{H}_n, \mathbf{g}_{R,Q}]$ after adding the transmit antenna Q , and then becomes $\mathbf{H}_{n+1} = [\tilde{\mathbf{H}}_n^T, \mathbf{h}_{P,\mathbf{r}}^T]^T$ after adding the receive antenna P . Thus, the channel capacity can be expressed as

$$\begin{aligned} C(\mathbf{H}_{n+1}) &= \log_2 \det \left(\mathbf{I}_{n+1} + \frac{\rho}{n+1} \mathbf{H}_{n+1} \mathbf{H}_{n+1}^H \right) \\ &= \log_2 \det \left\{ \mathbf{I}_{n+1} + \frac{\rho}{n+1} \begin{bmatrix} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H & \tilde{\mathbf{H}}_n \mathbf{h}_{P,\mathbf{r}}^H \\ \mathbf{h}_{P,\mathbf{r}} \tilde{\mathbf{H}}_n^H & \mathbf{h}_{P,\mathbf{r}} \mathbf{h}_{P,\mathbf{r}}^H \end{bmatrix} \right\}. \end{aligned} \quad (4)$$

Using $\det \begin{pmatrix} \mathbf{X} & \mathbf{Y} \\ \mathbf{Z} & \mathbf{W} \end{pmatrix} = \det(\mathbf{X}) \det(\mathbf{W} - \mathbf{Z}\mathbf{X}^{-1}\mathbf{Y})$, Ep. (4) is further formulated as

$$\begin{aligned} C(\mathbf{H}_{n+1}) &= \log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n+1} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H \right) \\ &\quad + \log_2 \left[1 + \frac{\rho}{n+1} |\mathbf{h}_{P,\mathbf{r}}|^2 - \frac{\rho^2}{(n+1)^2} \mathbf{h}_{P,\mathbf{r}} \tilde{\mathbf{H}}_n^H \right. \\ &\quad \left. \left(\mathbf{I}_n + \frac{\rho}{n+1} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H \right)^{-1} \tilde{\mathbf{H}}_n \mathbf{h}_{P,\mathbf{r}}^H \right]. \end{aligned} \quad (5)$$

As $\tilde{\mathbf{H}}_n = [\mathbf{H}_n, \mathbf{g}_{R,Q}]$, then

$$\begin{aligned} \frac{\rho}{n+1} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H &= \frac{\rho}{n+1} \mathbf{H}_n \mathbf{H}_n^H + \frac{\rho}{n+1} \mathbf{g}_{R,Q} \mathbf{g}_{R,Q}^H \\ &= \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H - \frac{\rho}{n(n+1)} \mathbf{H}_n \mathbf{H}_n^H + \frac{\rho}{n+1} \mathbf{g}_{R,Q} \mathbf{g}_{R,Q}^H. \end{aligned} \quad (6)$$

Using $\det(\mathbf{X} + \mathbf{Y}) = \det(\mathbf{X}) \det(\mathbf{I} + \mathbf{X}^{-1}\mathbf{Y})$, we obtain

$$\begin{aligned} \log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n+1} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H \right) &= \log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H \right) \\ &\quad + \log_2 \det \left(\mathbf{I}_n + \left(\mathbf{I}_n + \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H \right)^{-1} \right. \\ &\quad \left. \left(\frac{\rho}{n+1} \mathbf{g}_{R,Q} \mathbf{g}_{R,Q}^H - \frac{\rho}{n(n+1)} \mathbf{H}_n \mathbf{H}_n^H \right) \right). \end{aligned} \quad (7)$$

To make the notation easier to read, we define

$$\mathbf{B}_{n,n} = \left(\mathbf{I}_n + \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H \right)^{-1}, \quad \mathbf{D}_{n,n} = \left(\mathbf{I}_n + \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H \right)^{-1}. \quad (8)$$

It is noted that m is a variable. Thus, the channel capacity in the $(n+1)$ th step is finally written as

$$\begin{aligned} C(\mathbf{H}_{n+1}) &= C(\mathbf{H}_n) + \log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n} \mathbf{H}_n \mathbf{H}_n^H \right) \\ &\quad + \log_2 \left(1 + \frac{\rho}{n+1} |\mathbf{h}_{P,\mathbf{r}}|^2 - \frac{\rho^2}{(n+1)^2} \mathbf{h}_{P,\mathbf{r}} \tilde{\mathbf{H}}_n^H \mathbf{D}_{n,n+1} \tilde{\mathbf{H}}_n \mathbf{h}_{P,\mathbf{r}}^H \right). \end{aligned}$$

Thus, the channel capacity increase after adding transmit antenna Q and receive antenna P in the $(n+1)$ th step is

$$\begin{aligned} \Delta C_{(P,Q)(n+1)} &= C(\mathbf{H}_{n+1}) - C(\mathbf{H}_n) \\ &= \log_2 \det \left(\mathbf{I}_n + \underbrace{\mathbf{B}_{n,n} \left(\frac{\rho}{n+1} \mathbf{g}_{R,Q} \mathbf{g}_{R,Q}^H - \frac{\rho}{n(n+1)} \mathbf{H}_n \mathbf{H}_n^H \right)}_{\alpha_n} \right) \\ &\quad + \log_2 \left[\underbrace{1 + \frac{\rho}{n+1} |\mathbf{h}_{P,\mathbf{r}}|^2 - \frac{\rho^2}{(n+1)^2} \mathbf{h}_{P,\mathbf{r}} \tilde{\mathbf{H}}_n^H \mathbf{D}_{n,n+1} \tilde{\mathbf{H}}_n \mathbf{h}_{P,\mathbf{r}}^H}_{\beta_n} \right]. \end{aligned} \quad (9)$$

The antenna selection criterion in the $(n+1)$ th step is to choose the transmit and receive antenna pair (P^*, Q^*) that maximize the capacity increase, i.e.,

$$(P^*, Q^*) = \arg \max_{Q \in \mathbf{S}_T, P \in \mathbf{S}_R} \Delta C_{(P,Q)(n+1)}. \quad (10)$$

3.2 Proposed Algorithm

Though Eq. (9) gives the closed form of channel capacity increase when one more pair of transmit and receive antennas are added, it contains the computation of the matrix α_n , which makes the computational complexity higher. However, we are just interested in finding the pair of transmit and receive antennas that make the maximal channel capacity increase in every step and not about the amount of the capacity increases. For the decrease in the computation complexity, define the pseudo-channel capacity as

$$\Xi(\mathbf{H}_n) = \log_2 \left[\det \left(\mathbf{I}_n + \frac{\rho}{n+1} \mathbf{H}_n \mathbf{H}_n^H \right) \right]. \quad (11)$$

By plugging $\tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H = \mathbf{H}_n \mathbf{H}_n^H + \mathbf{g}_{R,Q} \mathbf{g}_{R,Q}^H$ into Eq. (7), Eq. (7)

can be changed to

$$\log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n+1} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H \right) = \log_2 \det \left(\mathbf{I}_n + \frac{\rho}{n+1} \mathbf{H}_n \mathbf{H}_n^H \right) + \log_2 \left(1 + \mathbf{g}_{\mathbf{R},Q}^H \left(\mathbf{I}_n + \frac{\rho}{n+1} \mathbf{H}_n \mathbf{H}_n^H \right)^{-1} \mathbf{g}_{\mathbf{R},Q} \right) \quad (12)$$

Thus the pseudo-channel capacity increase is

$$\begin{aligned} \Delta \Xi_{(P,Q)(n+1)} &= C(\mathbf{H}_{n+1}) - \Xi(\mathbf{H}_n) \\ &= \log_2 \left(1 + \frac{\rho}{n+1} \mathbf{g}_{\mathbf{R},Q}^H \mathbf{B}_{n,n+1} \mathbf{g}_{\mathbf{R},Q} \right) + \log_2 [1 \\ &\quad + \frac{\rho}{n+1} |\mathbf{h}_{P,\hat{\mathbf{T}}}^2 - \frac{\rho^2}{(n+1)^2} \mathbf{h}_{P,\hat{\mathbf{T}}} \tilde{\mathbf{H}}_n^H \mathbf{D}_{n,n+1} \tilde{\mathbf{H}}_n \mathbf{h}_{P,\hat{\mathbf{T}}}^H] \end{aligned} \quad (13)$$

And the best pair of transmit and receive antennas are those that

$$(P, Q) = \arg \max_{q \in \mathbf{S}_T, p \in \mathbf{S}_R} \Delta \Xi_{(p,q)(n+1)} \quad (14)$$

Using Eq. (13) for antenna selection avoids the computation of $\det(\alpha_n)$. However, we still need to compute the matrices $\mathbf{B}_{n,n+1}$ and $\mathbf{D}_{n,n+1}$. In the n -th step (n is known), we first express $\mathbf{B}_{n,m}$ and $\mathbf{D}_{n,m}$ in Eq. (8) as a function of m , and then set $m = n+1$ to calculate $\mathbf{B}_{n,n+1}$ and $\mathbf{D}_{n,n+1}$.

Assume that we have obtained $\mathbf{B}_{n,m}$ and $\mathbf{D}_{n,m}$ in the n -th step, $\mathbf{B}_{n+1,m}$ and $\mathbf{D}_{n+1,m}$ in the $(n+1)$ th step can be obtained recursively. From Eq. (8), we get

$$\begin{aligned} \mathbf{B}_{n+1,m} &= (\mathbf{I}_{n+1} + \frac{\rho}{m} \mathbf{H}_{n+1} \mathbf{H}_{n+1}^H)^{-1} \\ &= \begin{bmatrix} \mathbf{I}_n + \frac{\rho}{m} \tilde{\mathbf{H}}_n \tilde{\mathbf{H}}_n^H & \frac{\rho}{m} \tilde{\mathbf{H}}_n \mathbf{h}_{p,\hat{\mathbf{T}}}^H \\ \frac{\rho}{m} \mathbf{h}_{p,\hat{\mathbf{T}}} \tilde{\mathbf{H}}_n^H & 1 + \frac{\rho}{m} \mathbf{h}_{p,\hat{\mathbf{T}}} \mathbf{h}_{p,\hat{\mathbf{T}}}^H \end{bmatrix}^{-1} \end{aligned} \quad (15)$$

After matrix computation, we define $\mathbf{B}_{n+1,m}$ and $\mathbf{D}_{n+1,m}$ can be updated using $\mathbf{D}_{n,m}$ as

$$\mathbf{B}_{n+1,m} = \begin{bmatrix} \mathbf{D}_{n,m} & \mathbf{0}_{n \times 1} \\ \mathbf{0}_{1 \times n} & 0 \end{bmatrix} + \frac{1}{\beta_n} \begin{bmatrix} \mathbf{f}_p & -\mathbf{f}_p \\ -\mathbf{f}_p^H & 1 \end{bmatrix} \quad (16)$$

According to the Sherman-Morrison formula [11] for determinants, $\mathbf{D}_{n+1,m}$ can be updated using $\mathbf{B}_{n+1,m}$ as

$$\begin{aligned} \mathbf{D}_{n+1,m} &= \left(\mathbf{I}_{n+1} + \frac{\rho}{m} \tilde{\mathbf{H}}_{n+1} \tilde{\mathbf{H}}_{n+1}^H \right)^{-1} \\ &= \left(\mathbf{I}_{n+1} + \frac{\rho}{m} \mathbf{H}_{n+1} \mathbf{H}_{n+1}^H + \frac{\rho}{m} \mathbf{g}_{\mathbf{R},q} \mathbf{g}_{\mathbf{R},q}^H \right)^{-1} \\ &= \mathbf{B}_{n+1,m} - \frac{\frac{\rho}{m} \mathbf{g}_{\mathbf{R},q} \mathbf{g}_{\mathbf{R},q}^H \mathbf{B}_{n+1,m}}{\frac{\rho}{m} + \mathbf{g}_{\mathbf{R},q}^H \mathbf{B}_{n+1,m} \mathbf{g}_{\mathbf{R},q}}. \end{aligned} \quad (17)$$

Overall, we can obtain $\mathbf{B}_{n,m}$ and $\mathbf{D}_{n,m}$ recursively for n from 1 to n_m . For each specific step n , $\mathbf{B}_{n,m}$ and $\mathbf{D}_{n,m}$ can be used for computing of $\mathbf{B}_{n,n+1}$ and $\mathbf{D}_{n,n+1}$ in Eq. (13) by setting $m = n+1$, as well as for further recursion, i.e., $\mathbf{B}_{n+1,m}$ and $\mathbf{D}_{n+1,m}$.

In the first step of the proposed algorithm, the selected pair of transmit and receive antennas corresponds to the channel coefficient with the maximum norm and the complexity is $O(N_T N_R)$. In the other $n_m - 1$ steps, the $n_m - 1$

pairs of antennas are selected; the main computation complexity of this step is in Eq. (13), as the matrix $\mathbf{B}_{n,m}$ and $\mathbf{D}_{n,m}$ can be updated using Eqs. (16) and (17), the computation complexity of selecting the $(n+1)$ th ($2 \leq n \leq n_m$) pair of transmit and receive antennas reduced from $O(n^3)$ to $O(n^2)$. Therefore, the computation complexity of the algorithm is

$$\begin{aligned} \Psi &= O(N_T N_R) + \sum_{n=2}^{n_m} (N_T - n + 1) O((n+1) O((n-1)^2)) \\ &= O(N_T N_R n_m^3). \end{aligned}$$

Compared with the computation complexity of the optimal solution $O(N_T^{n_m} N_R^{n_m} n_m^3)$ and the simplified algorithm in [9] $O(N_T^{n_m} N_R n_m^2 + N_R^{n_m} n_m^3)$, the computation complexity of the new proposed algorithm is smaller.

4. Simulation Results

The simulation results show ergodic capacity and outage capacity performance of the MIMO system in i.i.d. Rayleigh fading channels with the RAS algorithm proposed in [9], [10]. The performance of the two algorithms in [9] and [10] is the same, so we just plot one curve in the simulation results. Also, the RAS and the NBS algorithms are compared with the proposed algorithm. We assume that the transmitter and receiver are equipped with the same number of antennas. The simulation results are obtained by averaging the instantaneous capacity of the selected channel matrices. We consider a total of 2000 experiments for each algorithm. Figure 1 shows the ergodic capacity versus different number of antennas for various algorithms when the numbers of RF chains are fixed to 2 and 4, and SNR is set to 10 dB. For the convenience of simulation, we assume the transmitter and receiver equipped with the same number of antennas. As the antenna number increases, the DTRAS algorithm shows an increasing performance loss when compared with the optimal system performance. Compared with DTRAS algorithm, the new proposed algorithm is close to the optimal. It achieves the gain of 1.5 bits/Hz/Sec when the number of RF chains is 4 and 1 bit/Hz/Sec when the number of RF chains is 2 at large antenna number values.

Fig. 1 Capacity performance vs. the number of antennas.

Fig. 2 Outage capacity vs. outage probability.

Though the NBS algorithm is simple, as we can see in the simulation, the performance loss is very large as compared with DTRAS and the proposed algorithm. The NBS algorithm is better than the MIMO system with only receive antenna selection, but the predominance becomes neglectable as the number of antenna becomes large. Figure 2 shows the outage capacity of the communication systems with 10 receive antennas, 8 transmit antennas and 2 RF chains at both sides, SNR is set to 20 dB. The performance difference between DTRAS algorithms and the new proposed algorithm increases as the outage probability decreases. When the outage probability is zero, the performance loss of the DTRAS algorithms is more than 0.5 bits/Hz/Sec as compared with the optimal performance while the new algorithm presents no more than 0.1 bits/Hz/Sec. Though Fig. 1 shows that the ergodic capacity of the MIMO system when using NBS algorithm is better than RAS, in this figure we can see that as the outage probability becomes lower, the capacity loss when using NBS algorithm becomes more significant. If the system performance requires an outage probability less than 15%, the performance of the system with NBS algorithm will be worse than the RAS system.

5. Conclusions

A new iterative transmit/receive antenna selection algorithm was proposed in this paper. The objective is to obtain the optimal transmit/receive antenna subset to maximize

system capacity. To avoid the prohibitive realize computational complexity of the exhaustive search antenna selection algorithm and also the performance loss of the DTRAS algorithms, the new proposed algorithm using incremental selection algorithm, every step one more pair of transmit and receive antennas was selected simultaneously. As the results show, the new algorithm achieves near-optimal performance, and is better than other conventional antenna selection algorithms at the cost of adding some computation complexity to the system.

References

- [1] T.L. Marzetta and B.M. Hochwald, "Capacity of a mobile multiple-antenna communication link," *IEEE Trans. Inf. Theory*, vol.45, no.1, pp.139–157, Jan. 1998.
- [2] G. Foschini and M.J. Ganss, "On limits of wireless communications in a Rayleigh environment when using multiple antennas," *Wirel. Pers. Commun.*, vol.6, no.3, pp.311–335, March 1998.
- [3] A.F. Molisch, "MIMO with antenna selection—An overview," *Radio and Wireless Conference*, pp.167–170, Aug. 2003.
- [4] S. Sanayei and A. Nosratinia, "Antenna selection in MIMO systems," *IEEE Commun. Mag.*, vol.42, no.10, pp.68–73, Oct. 2004.
- [5] J. Chen, J. Yuan, B. Vucetic, and Z. Zhou, "Performance of Alamouti scheme with transmit antenna selection," *Electron. Lett.*, vol.29, no.13, pp.1666–1668, Nov. 2003.
- [6] P. Schnitzler, L.M. Garth, and M. Dohler, "An analysis of low-complexity algorithms for MIMO antenna selection," *IEEE Inter. Conf. Commun.*, vol.3, pp.1380–1385, June 2006.
- [7] A. Gorokhov, D. Gore, and A. Paulraj, "Receive antenna selection for MIMO spatial multiplexing: Theory and algorithms," *IEEE Trans. Signal Process.*, vol.51, no.11, pp.2796–2807, Nov. 2003.
- [8] M. Gharavi-Alkhansari and A.B. Gershman, "Fast antenna subset selection in MIMO systems," *IEEE Trans. Signal Process.*, vol.52, no.2, pp.339–347, Feb. 2004.
- [9] A. Gorokhov, M. Collados, D. Gore, and A. Paulraj, "Transmit/receive MIMO antenna subset selection," *IEEE Inter. Conf. Acoustics, Speech, and Signal Processing*, vol.2, pp.13–16, May 2004.
- [10] S. Sanayei and A. Nosratinia, "Capacity maximizing algorithms for joint transmit-receive antenna selection," *Proc. 38th Asilomar Conference on Signals, Systems and Computers*, pp.1773–1776, Nov. 2004.
- [11] G. Kéri, The Sherman-Morrison formula for the determinant and its application for optimizing quadratic functions on condition sets given by extreme generators, in *Optimization Theory: Recent Developments from Mátraháza*, eds. F. Giannessi, P. Pardalos, and T. Rapcsk, Kluwer, Boston, MA, 2001.