J Shanghai Univ (Engl Ed) (2008) 12(1): 61–65
Digital Object Identifier(DOI): 10.1007/s 11741-008-0112-2

# Closed-loop transmit diversity systems with hybrid antenna selection

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**Abstract** The paper investigates closed-loop transmit diversity (CLTD) systems with antenna selection technique. The expected received signal-noise-ratio (RxSNR) of the proposed systems is analyzed and compared with CLTD systems. An algorithm is proposed for determining the number of increased transmit antennas in terms of a reduced RF chains without performance degradation. Since a feedback channel is bandwidth-limited, we present a method of quantizing transmit-weight vectors. Simulation results demonstrate advantage of the proposed systems with full and quantized feedback information. Quantized feedback has less effect on the proposed systems than CLTD systems.

**Keywords** antenna selection, closed-loop transmit diversity (CLTD), quantized feedback.

## 1 Introduction

The next generation wireless communication systems are required to provide high quality voice services as well as broadband data services. To achieve this goal, a key technique employed in the emerging wireless systems is transmit diversity.

Transmit diversity systems can be classified into open-loop systems and closed-loop systems. The open-loop transmit diversity systems[1,2], which operate without any feedback information from the mobile, are known to offer diversity gain. The closed-loop transmit diversity (CLTD) systems[3,4], which operate with feedback information from the mobile, offer not only diversity gain but also beamforming gain. These two transmit diversity systems can provide significant increases in system capacity and performance, but they are both characterized by a relatively higher implementation complexity than antenna selection diversity. Recently, there have been some attempts in combining space-time coding systems with antenna selection technique to reduce the system complexity[5–7]. However, the combination of space-time coding and antenna selection does not take full advantage of channel state information (CSI) available at the transmitter. Murthy[8] and Pan[9] proposed to combine CLTD systems with antenna selection, called ASCLTD systems for brevity. Antenna selection and CLTD can share the feedback channel for CSI which can determine optimum selection of antennas in addition to optimum transmit-weight vector. This approach reduces the implemental complexity of CLTD systems in practice while still having benefits of multiple antennas.

This paper explores the antenna selection algorithm for closed-loop transmit diversity systems. The purpose is to reduce the number of RF chains with the same performance. The algorithm for determining the number of increased antennas is given. We present the algorithm of quantizing transmit-weight vectors corresponding to optimal channel vectors. Simulation results verify the advantages of ASCLTD systems in both implemental complexity and performance improvement.

## 2 Problem statements

We consider a wireless link in a quasi-static flat Rayleigh fading environment with $M_{\mathrm{T}}$ antennas and $M_{\mathrm{F}}$ RF chains on the transmitter side and one antenna on the receiver side. Let $\boldsymbol{h}$ denote the $1 \times M_{\mathrm{T}}$ channel vector. Its entries are the fading coefficients $h_i$, which are modeled as independent samples of complex Gaussian random variables with a zero mean and variance of 0.5 per dimension. It is assumed that CSI is perfectly available at the receiver and full or partially known at the transmitter. For CLTD systems, transmit-weight vector $\boldsymbol{w}$ is calculated at the receiver with CSI, and fed back to the transmitter. At the transmitter, the data symbol is multiplied by these weight vectors before transmission. For the antenna selection algorithm, $M_{\mathrm{F}}$ ($M_{\mathrm{F}} < M_{\mathrm{T}}$) transmit antennas are chosen and activated for transmission and the other antennas are silent. The selection criterion has to be determined according to the specific system. The baseband equivalent model of ASCLTD systems is shown in Fig.1. The received signal may be

Received Aug.10, 2006; Revised Oct.25, 2006
Project supported by the National Natural Science Foundation of China (Grant No.60472103), the Shanghai Excellent Academic Leader Project (Grant No.05XP14027), and the Shanghai Leading Academic Discipline Project (Grant No.T0102)
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expressed as

$$x = \sqrt{E_S} \boldsymbol{h}_p^{\mathrm{H}} \boldsymbol{w} s + n, \tag{1}$$

where $E_S := E\{|s|^2\}$ is the average energy of the underlying signal constellation, H in the superscript denotes Hermitian transpose, $n$ is a complex additive white Gaussian noise for receive antenna, $\boldsymbol{w} = [w_1\ w_2\ \cdots\ w_{M_F}]^{\mathrm{H}}$ denotes transmit-weight vector. A $1 \times M_F$ channel $\boldsymbol{h}_p$, which is the optimal subset $p \in \{1, 2, \cdots, P\}$ out of all possible $P = C_{M_T}^{M_F}$ subsets of $\boldsymbol{h}$, is used to denote the channel between $M_F$ chosen transmit antennas and one receive antenna. To maintain the same transmit power, we normalize transmit-weight vector such that $\|\boldsymbol{w}\|^2 \triangleq \sum\limits_{m=1}^{M_F} |w_m|^2 = 1$.

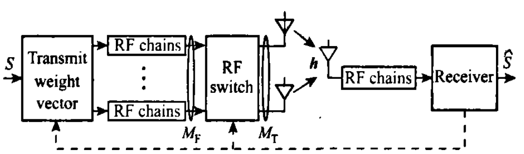


**Fig.1** System model

Comparing to $M$ diversity CLTD systems, the $(M_F, M_T)$ ASCLTD systems use $M_F$ ($M_F < M$) reduced RF chains by installing $M_T$ ($M_T > M$) increased transmit antennas. Obviously, only using $M_F$ RF chains will lead to performance loss. Then the value of increased transmit antennas is sufficient to compensate for the loss. The algorithm of determining the value of $M_T$ is our concern. Transmit-weight vectors are calculated by receiver to maximize RxSNR, and are periodically fed back to transmitter through feedback channel. However, the bandwidth of feedback channel limits the precision of these weight vectors. Our task is to quantize these weight vectors and minimize the performance loss.

## 3 Computation of increased transmit antennas number

For each channel realization of $\boldsymbol{h}_p$, the SNR at the receiver output (RxSNR) is

$$\gamma_{\mathrm{ASCLTD}} = (E_S/N_0)|\boldsymbol{h}_p^{\mathrm{H}} \boldsymbol{w}|^2 = \gamma_0 \boldsymbol{w}^{\mathrm{H}} \boldsymbol{R}_p \boldsymbol{w}, \tag{2}$$

where $\gamma_0 = E_S/N_0$ denotes transmit SNR (TxSNR) and $\boldsymbol{R}_p = \boldsymbol{h}_p \boldsymbol{h}_p^{\mathrm{H}}$ is an $M_F \times M_F$ Hermitian matrix. An optimum transmit-weight vector can be obtained by finding $\boldsymbol{w}$ which maximizes RxSNR in (2). With the Rayleigh-Ritz theorem[10], optimum weight vector $\boldsymbol{w}_{\mathrm{opt}}$ is a principal eigenvector which is associated with maximum eigenvalue of $\boldsymbol{R}_p$. Thus, the optimum RxSNR may be expressed as

$$\gamma_{\mathrm{ASCLTD}}^{\mathrm{opt}} = \gamma_0 \|\boldsymbol{h}_p\|^2 = \gamma_0 \sum_{i=1}^{M_F} |h_{\mathrm{pi}}|^2, \tag{3}$$

where $|h_{\mathrm{pi}}|^2, \mathrm{pi} = 1, \cdots, M_T$, are i.i.d. chi-squared variables[11] with probability density function (p.d.f) given by

$$f(z) = f(|h_{\mathrm{pi}}|^2 = z) = \mathrm{e}^{-z}, \tag{4}$$

and cumulative distribution function (c.d.f.) given by

$$F(z) = P(|h_{\mathrm{pi}}|^2 \leqslant z) = 1 - \mathrm{e}^{-z}. \tag{5}$$

The channel parameters are random, thus the system performance measured by SNR is a random variable. In such cases, the expected SNR provides the corresponding measures of average performance of interest in such systems. Irrespective of the TxSNR, the average of optimal RxSNR has been

$$\bar{\gamma}_{\mathrm{ASCLTD}}^{\mathrm{opt}} = \varepsilon\{\gamma_{\mathrm{AS}}^{\mathrm{opt}}\}/\gamma_0 = \sum_{i=1}^{M_F} \varepsilon\{|h_{\mathrm{pi}}|^2\}. \tag{6}$$

Optimal antenna subset is chosen to maximize the instantaneous SNR. In (6), the selection algorithm will choose the transmit antennas among the $M_F$ highest $|h_{\mathrm{pi}}|^2$. We produce a new set of descended variables $X_k, k = 1, \cdots, M_F$ from $|h_{\mathrm{pi}}|^2$. $X_k$ is the $k$th largest of $M_T$ random variables. Then (6) is rewritten as follows:

$$\bar{\gamma}_{\mathrm{ASCLTD}}^{\mathrm{opt}} = \varepsilon\{X_1\} + \cdots + \varepsilon\{X_{M_F}\}. \tag{7}$$

Then based on [12], the p.d.f. of $X_k$ is

$$p(x) = C_{M_T}^{k-1}[1 - F(x)]^{k-1} C_{M_T-k+1}^{1} \cdot f(x)[F(x)]^{M_T-k}. \tag{8}$$

Therefore, the average of $k$th highest statistic $X_k$ is

$$\varepsilon\{X_k\} = M_T C_{M_T-1}^{k-1} \sum_{r=0}^{M_T-k} \Big[(-1)^{M_T-k-r} \cdot C_{M_T-k}^{r} (M_T - r)^{-2}\Big], \tag{9}$$

and the average of optimal RxSNR has been

$$\bar{\gamma}_{\mathrm{ASCLTD}}^{\mathrm{opt}} = \sum_{k=1}^{M_F} \Big\{ M_T C_{M_T-1}^{k-1} \sum_{r=0}^{M_T-k} \Big[(-1)^{M_T-k-r} \cdot C_{M_T-k}^{r} (M_T - r)^{-2}\Big]\Big\}. \tag{10}$$

When $M_T = M_F = M$, the systems become pure CLTD systems. The average of its optimum RxSNR can be expressed as follows:

$$\bar{\gamma}_{\mathrm{CLTD}}^{\mathrm{opt}} = \sum_{i=1}^{M} \varepsilon\{|h_{\mathrm{pi}}|^2\} = M. \tag{11}$$

Equation (11) gives the performance measure for CLTD systems. This is interest result that the average of optimum RxSNR of CLTD systems is equal to its diversity number. Nowadays, we hope to employ a reduced RF chains. We want to compute the number of increased transmit antennas which can compensate performance loss from a reduced RF chains. In other words, we hope

$$M_{\mathrm{F}} < M < M_{\mathrm{T}}, \tag{12}$$

guaranteeing

$$\bar{\gamma}^{\mathrm{opt}}_{\mathrm{ASCLTD}} \geqslant \bar{\gamma}^{\mathrm{opt}}_{\mathrm{CLTD}}. \tag{13}$$

Combining (10)~(13), the solution is obtained.

## 4 Quantization of transmit-weight vectors

The feedback channel is bandwidth-limited, therefore transmit-weight vectors must be quantized. There are two selections in ASCLTD systems. One is the selection of optimum transmit antenna subset. The $M_{\mathrm{F}}$ highest $|h_{\mathrm{p}i}|^2$ was chosen from $M_{\mathrm{T}}$ transmit antennas, then selection criterion may be expressed as

$$\boldsymbol{h}_p = \max_{p\in P} \|\boldsymbol{h}_p\|^2. \tag{14}$$

The other is the selection of optimum quantized weight vector. Grassmannian subspace packing[13–15] can be used to quantize weight vectors. The Grassmannian space $g(M_{\mathrm{F}}, n)$ is the set of all $n$ dimensional subspaces of $M_{\mathrm{F}}$ dimensional space. The Grassmannian packing is the problem of finding the best packing of $Q$ $n$-dimensional subspace in $M_{\mathrm{F}}$ dimensional space. That is to say, we hope to find $Q$ points in $g(M_{\mathrm{F}}, n)$ so that the minimal distance between any two of them is as large as possible. Since we only concern with $g(M_{\mathrm{F}}, 1)$, the subspaces become lines such that the angle between any two of the lines becomes as large as possible[13]. Thus the problem simplifies down to arranging $Q$ vectors so that the magnitude correlation between any two lines is as small as possible.

Finding good precoder codebooks from Grassmannian subspace packing for arbitrary $M_{\mathrm{F}}, n$, and $Q$ is actually quite troublesome. The most feasible method for generating these packings is to use codebooks designed from the noncoherent space-time modulation designs in [14,15].

The search algorithm in [14] can be very easily implemented and yields codebooks with large minimum distances. The algorithm works by considering codebooks of the form

$$\Omega = \{\boldsymbol{w}_{\mathrm{DFT}}, \boldsymbol{\theta}\boldsymbol{w}_{\mathrm{DFT}}, \cdots, \boldsymbol{\theta}^{Q-1}\boldsymbol{w}_{\mathrm{DFT}}\}, \tag{15}$$

where $\boldsymbol{w}_{\mathrm{DFT}}$ is an $M_{\mathrm{F}} \times 1$ vector with $\frac{1}{\sqrt{M_{\mathrm{F}}}}\mathrm{e}^{\mathrm{i}(2\pi/M_{\mathrm{F}})k}$ at the $k$th entry, the $q$th codebook is $\boldsymbol{w}_q = \boldsymbol{\theta}^{q-1}\boldsymbol{w}_{\mathrm{DFT}}$, and $\boldsymbol{\theta}$ is a diagonal matrix given by

$$\theta_{kk} = \mathrm{e}^{\mathrm{i}(2\pi/Q)u_k}, \quad k = \{1, 2, \cdots, M_{\mathrm{F}}\}, \tag{16}$$

where $0 \leqslant u_k \leqslant Q-1$.

The values for $u_1, u_2, \cdots, u_{M_{\mathrm{F}}}$ are determined in terms of the entries of the vector $\boldsymbol{u} = [u_1, u_2, \cdots, u_{M_{\mathrm{F}}}]^{\mathrm{T}}$ from the set $Z = \{\boldsymbol{u} \in Z^{M_{\mathrm{F}}} | \forall k, 0 \leqslant u_k \leqslant Q-1\}$ given by

$$\boldsymbol{u} = \arg\max_{Z} \min_{1\leqslant l\leqslant Q-1} d(\boldsymbol{w}_{\mathrm{DFT}}, \boldsymbol{\theta}^l \boldsymbol{w}_{\mathrm{DFT}}). \tag{17}$$

At present, the codebooks of quantized precoder are available. For each optimum channel vector $\boldsymbol{h}_p$, the optimum quantized precoder $\boldsymbol{w}_q$ can be chosen to maximize the RxSNR. Namely,

$$\boldsymbol{w}_q = \max_{q\in\{1,\cdots,Q\}} |\boldsymbol{h}_p^{\mathrm{H}} \boldsymbol{w}_q|^2. \tag{18}$$

Comparing with CLTD systems, these quantized weight vectors come from optimum channel vector $\boldsymbol{h}_p$, not from random one. Therefore, the quantized weight vector matches employed channel vector more.

## 5 Simulations

First simulation is to illustrate the advantage of ASCLTD. In Section 3, we know that the average RxSNR of $M$ diversity CLTD systems is $\bar{\gamma}^{\mathrm{opt}}_{\mathrm{CLTD}} = M$. For $(M_{\mathrm{F}}, M_{\mathrm{T}})$ ASCLTD systems, the average RxSNR $\bar{\gamma}^{\mathrm{opt}}_{\mathrm{ASCLTD}}$ can be represented as (10). For visualization, we show performance of ASCLTD in Fig.2 for $M_{\mathrm{F}} = 1, \cdots, 6$. We find that the average RxSNR of a (5, 8) ASCLTD system is equal to 7.1726, greater than that with 7 diversity CLTD systems. In other words, one cheaper transmit antenna save two more expensive RF chains. This is an appealing characteristic.

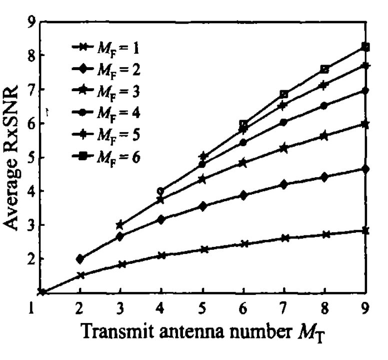


**Fig.2** Average RxSNR for ASCLTD systems

Due to the merit of ASCLTD, another problem is whether antenna selection technique can completely replace closed-loop technique. If $M_F = 1$, the system becomes pure transmit antenna selection systems whose performance is shown in Fig.3. The average RxSNR with 4 transmit antennas is slightly larger than 2, and the average RxSNR with 11 transmit antennas is slightly larger than 3. If the average RxSNR is to exceed 4, 31 transmit antennas are required. Obviously, only by transmit antenna selection, abundant transmit antennas are a considerable burden and make antenna switch very difficult. Therefore, it is impractical to entirely depend on the antenna selection technique.

The second simulation is to compare RxSNR between 7 diversity CLTD systems and the (5,8) ASCLTD systems under full and quantized feedback. Channel realizations are i.i.d. from frame to frame. Simulation result with 128 channel realizations is shown in Fig.4, which only displays 40 realizations for clarity. RxSNR of the ASCLTD systems is sometimes higher than that of CLTD systems, and sometimes lower. However, average RxSNR of ASCLTD is slightly higher than that of CLTD, which is consistent with the theoretic result. At present, we investigate the effect from quantized feedback. Here we adopt $N = 4$ bits to encode $Q = 16$ quantized transmit-weight vector[16]. Then system performance will be degenerated due to quantized feedback as shown in Fig.4, where GPS is an abbreviation of Grassmannian subspace packing. Fortunately, RxSNR of ASCLTD is considerably higher than that of CLTD under quantized feedback.

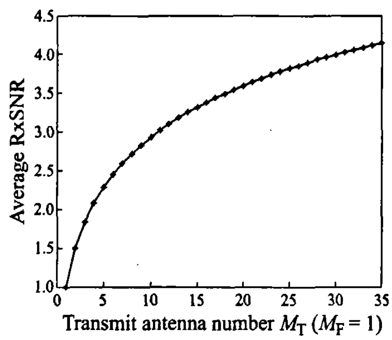


**Fig.3** Average RxSNR for pure transmit antenna selection

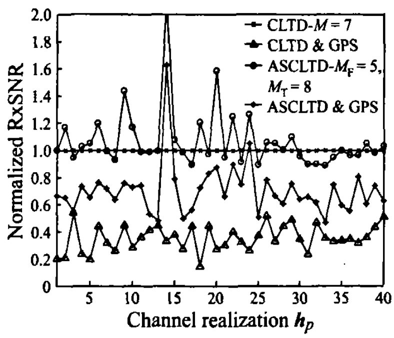


**Fig.4** Performance comparison of 4 systems

## 6 Conclusions

In this paper, we combine CLTD systems with antenna selection. An algorithm for determining the number of increased transmit antennas is given in terms of reduced RF chains without performance degradation. The solution of quantizing transmit-weight vectors is presented. Finally we simulate performance of ASCLTD and CLTD systems under full and quantized feedback. In some cases, one more transmit antenna can get two RF chains in return in ASCLTD systems. If we employ antenna selection as an alternative to CLTD, excessive transmitting antennas become a considerable obstacle. Compared to CLTD systems, quantized feedback has little effect on ASCLTD. Therefore, ASCLTD systems with quantized feedback can save the RF chains, and lessen the effect from quantized feedback as well.

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(Editor HONG Ou)

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