Multi-antenna Single-relay System Precoding Based on New Vector Quantization Method

Chaoyi ZHANG, Ruirui ZHANG*, Yan YAO

***Abstract*—**In order to solve receiver node can not acquire a perfect channel state information (CSI) problem in existing relay system, this paper uses a limited feedback idea, receiver sends parts of CSI to transmitter, then based on the existing MIMO knowledge, source node imports a time-domain precoding matrix. With minimal loss of mutual information as system optimization objective, a new vector quantization (VQ) method is used to build a codebook, and together with average power distribution matrix to compose the precoding matrix. At last, the VQ conditions under low SNR and high SNR are analysed for more optimization. Simulation results show that, compare with tradition distributed precoding, the new VQ precoding can acquire higher capacity gain and have good system bit error rate performance.

***Keywords*—**Multi-realy system, vector quantization, codebook, limited feedback, precoding

I. Introduction

RELAY network is one of the most promising architecture for future wireless networks. The research of relay network [1] demonstrates that simultaneous using relays can extend cell coverage and enhance system capacity. Multi-Input-Multi-Output (MIMO) techniques have been proved to be important parts of the future wireless communication system [2]. Therefore, the MIMO relay system is much attractive now.

Usually, two-hop relay system is the basic form of relay network. When the relay is equipped with multiple antennas, it can obtain the backward channel (source-relay) and forward channel (relay-destination) state information, and there are many signal processing technologies can be used to improve system performance. Zero-Forcing (ZF) relaying protocol is presented in [3]-[4], where the ZF equalizer and precoding are both used at relay node. Other MIMO detections are also considered in two-hop relay system as backward and forward filters. The minimizing mean squared error (MMSE) relay strategy is presented in [5]-[6], where two MMSE filters are used at relay node. [7]-[8] has proposed a QR-decomposition(QRD)-based relay protocol, which deal with QRD of forward and backward channel matrices, the equivalent channel matrices which source node reach to destination node could be triangulation, so the multiple signals could be in same-phase stack at the destination node.

Precoding is a closed-loop link self-adaption technology, it requires sender knows channel state information (CSI). In cooperation relay system, with link number increasing, the CSI requirement is more complex. In a general way, precoding design is influenced by all links in the system [9-10]. The CSI feedback (shared) technology in cooperation relay system has became the focus of research community. [11] has designed one limited feedback codebook. [12] proposed that using a channel measurement phase and a information dissemination phase to realize multiple nodes sharing CSI. These CSI feedback (shared) methods are required consuming too much system resource. [13-15] has focus on the time-domain precoding techniques in multi-relay system, it mainly applied some traditional pre-coding techniques into the variety multi-relay system. This paper focus on the multi-antenna single-relay system which includes direct links, and uses the time-domain precoding techniques to improve relay system.

[16] has used Grassmannian packing to build precoding codebook matrix, it required the elements in channel matrix H satisfy independent and identically distributed (i.i.d.) condition, but if the feedback channel bandwidth is limited, and the antenna number is large, the channel matrix can not fed back to the relay node. This paper uses a new vector quantization (VQ) method to design the channel matrix, the new VQ method can be seen as a coding method---for input vector $\{x\}$, it can find a "codebook vector" $\{w(x)\}$, make it is the best approximate to the input vector, this is actually a data compression idea. In this paper, we use our designed VQ method to build codebook, research the relay network's precoding.

The paper is organized as follow. System model is described in section II. The MIMO precoding of vector quantization is presented in section III. Some numerical results and related analysis are given in section IV. section V concludes this paper.

Notations: A^H, A^{-1} and $\|A\|_F$ mean the conjugate-transpose, inverse and Frobenius norm of A, respectively. $[A]_{i,j}$ means the element on the i th row and j th column of A. I_m is the $m\times m$ identity matrix, $0_{m,n}$ means an

This work was supported in part by the National Key Laboratory Opening Task (KF2N2014W01-002), and Fundamental Research Funds for the Central Universities (2015ZCQ-GX-04).

Chaoyi Zhang and Ruirui Zhang are with the National Agricultural Intelligent Equipment Technology Research Center, Beijing 100097, China. (corresponding author phone: 086-010-5150-3991; e-mail: zhangrr@nercita.org.cn).

Yan Yao was with School of automation, Beijing University of Posts and Telecommunications, Beijing 100876, China. (e-mail: yaoyan_bupt@sina.com).

all-zero matrix. $\varepsilon(\cdot)$ means the mathematical expectation. u_m is the set of $m \times m$ unitary matrices.

II. System Model

The system model is shown in Fig.1. The single source node (S) communicates with the destination node (D) through one relay node (R). Here non-regenerative relay (AF) protocol is used. N_S (N_R , N_D) antennas are equipped in S (R , D) respectively. There is direct link between S and D, and also the signals can be transmitted through the relay node.

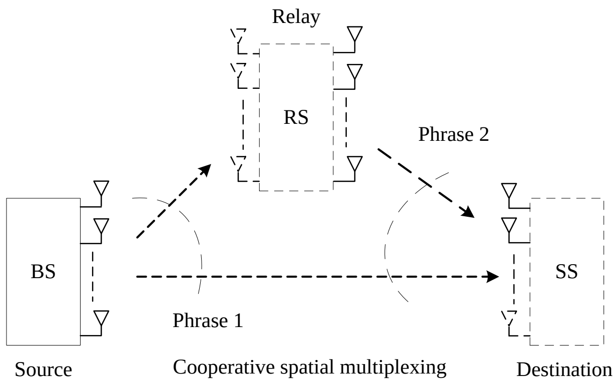

Fig.1 multi-antenna signal-relay system model

In phrase 1, S sends, R and D receive. The transmitted signal of S is x_{S1}, with the power constraint $E(\| x_S \|_F^2) = E_S$, $E(\bullet)$ is mathematical expectation, $\|\bullet\|_F$ is Forbenious norm. So, in phase 1, the received signal at R and D can be written as follow:

$$y_R = H_{SR} x_{S1} + n_R \tag{1}$$

$$y_{D1} = H_{SD} x_{S1} + n_{D1} \tag{2}$$

In phrase 2, S and R_i send, D receives. The transmitted signals of source node and relay are x_{S2} and x_R, so the received signal at D can be written as follow:

$$y_{D2} = H_{SD} x_{S2} + H_{RD} x_R + n_{D2} \tag{3}$$

In Eqs.(1)~(3), H_{SD} (H_{SR}, H_{RD}) are respectively the channel matrices of $S-D$ ($S-R$, $R-D$) links, n_{D1} (n_R, n_{D2}) are the Additive White Gaussian Noise (AWGN) of $S-D$ ($S-R$, $R-D$), $n_R \sim CN(0, \sigma_R^2 I_{N_R})$, n_{D1}, $n_{D2} \sim CN(0, \sigma_D^2 I_{N_D})$. S uses the spatial multiplexing (SM) protocol, so $E(x_S x_S^H) = E_S \cdot I$, I is the unit matrix.

without loss of generality (w.l.o.g.), assumption that $E_S = 1$, $\sigma_R^2 = \sigma_D^2 = \sigma^2$.

Because the AF relay protocol is used, so the signals which transmitted from R can be written as:

$$x_R = B \cdot y_R \tag{4}$$

Where B is the relay's transmitted matrix. Then Eqs.(1) and (4) are taken into Eq.(3):

$$y_{D2} = H_{SD} x_{S2} + H_{RD} B H_{SR} x_{S1} + H_{RD} B n_R + n_{D2} \tag{5}$$

Uniting Eqs.(2) and (5), the equivalent MIMO system can be obtained as:

$$\underbrace{\begin{bmatrix} y_{D1} \\ y_{D2} \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} H_{SD} & 0 \\ H_{RD} B H_{SR} & H_{SD} \end{bmatrix}}_{\mathbf{H}} \cdot \underbrace{\begin{bmatrix} x_{S1} \\ x_{S2} \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} n_{D1} \\ n_{D2} + H_{RD} B \cdot n_R \end{bmatrix}}_{\mathbf{n}} \tag{6}$$

So, if source node S obtains the equivalent channel matrix $\mathbf{H}$ and noise $\mathbf{n}$, some mature MIMO technologies can be used into this system model, such as precoding algorithm which based on channel right singular matrix.

Now, we acquire the relay virtual MIMO system model, and this applies to perfect CSI condition, however, in actual application environments, relay's CSI is mostly feedback from receiver, this determines relay can not acquire channel's perfect CSI, so research the precoding under imperfect CSI condition is more realistic.

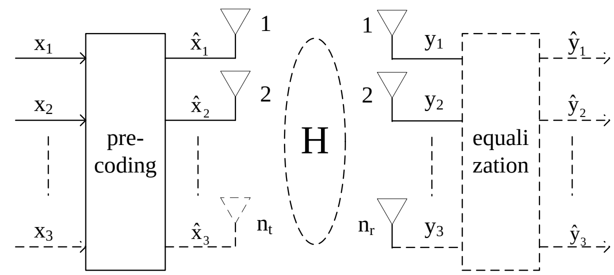

Fig.2 equivalent MIMO system

The equivalent virtual MIMO model of relay system is shown in Fig.2. "precoding" and "equalization" are respectively stand for the pre-coding processing and pre-equalization processing operation.

III. MIMO Precoding of Vector Quantization

Eq.(6) can be written as the following form:

$$y = Hx + n \tag{7}$$

In previous research, the MIMO system requires the elements in channel matrix H satisfy i.i.d. condition, but practical situation is rarely able to satisfy this requirement, for example, if H 's top right corner is 0 in Eq.(6), and it doesn't satisfy the i.i.d. requirement. In order to solve this problem, we add a precoding matrix in the relay, let matrix H left-multiply a precoding matrix F. So how to build this precoding matrix? This paper uses a limited feedback idea, proposes a new vector quantization (VQ) method to build a codebook, and obtains the precoding matrix at last.

The relay system is abstracted to a general MIMO system by Eq.(7), now we give the equivalent relay system model which include precoding matrix and limited feedback data, as shown in Fig.3.

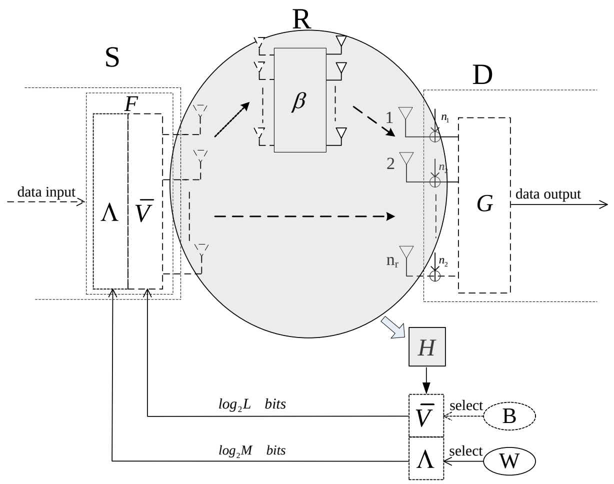

Fig.3 relay based on limited feedback (virtual MIMO model)

Fig.3 is a single-user MIMO model. The sender S and relay R are equipped with multiple antennas, the forwarding coefficient of R is β, AF protocol is used. The dashed circle is equivalent to the channel matrix H, the precoding matrix F is added in S, it is consist of limited feedback data which the receiver send to the sender according to H, this limited feedback idea reduces system's spectrum efficiency, it is also the approach under imperfect CSI. A pre-equalization matrix G is added in receiver D, it is used to balance the received signals. Now, we discuss the structure of precoding matrix F.

In Fig.3, the precoding matrix F is consist of a diagonal matrix Λ and a codebook $\bar{V}$, where the diagonal elements in Λ are sender power allocation values (here the average power allocation algorithm is used). Now the structure of codebook $\bar{V}$ is emphasis discussed, this paper uses VQ-based method, the specific process is as follow:

A MIMO precoding system is given:

$$y = HFx + n \tag{8}$$

Where, F is precoding matrix, it is also called as beamforming matrix, has $FF^H = I$; n is noise vector, and $n \sim CN(0, \sigma_n^2 I)$, the number of sender and relay is n_t, the receiver's antenna is n_r, the rank of channel matrix H is r, the singular value decomposition (SVD) to H is $H = UDV^H$. Because the average power allocation algorithm is used, each sender and relay's antenna transmitting power is $p = P_T / n_t$, from the information theory, it can acquire the system's mutual information:

$$I_{xy}(H,F) = \log_2 \det(I + pD^2 V^H FF^H V) \tag{9}$$

The optimized target is to maximize system's mutual information, and this is also maximize system capacity, now we take some changes to Eq.(9):

$$I_{xy}(H,F) = \log_2 \det(I + pD^2) + \log_2 \det[(I + (I + pD^2)^{-1} pD^2 (I - V^H FF^H V)] \tag{10}$$

In Eq.(10), The first part of the right-hand side is the channel total feedback information, the second part is the limited feedback, and this part causes some CSI loss. Then, the next step, the optimization target is to minimize the second part, denote as $I_{xy}(H,F)$, meanwhile, the next optimization is:

$$min \quad I_{xy}(H,F) = \log_2 \det[(I + \bar{D}^2 (I - V^H FF^H V)] \tag{11}$$

Where, $\bar{D}^2 = (I + pD^2)^{-1} pD^2$.

Under different transmitting power, $min\ I_{xy}(H,F)$ will have the following two different results:

1. when SNR is low. i.e. $P_T \ll 1$, $V^H FF^H V$ is close to the unit matrix, the feedback bits is large, CSI information is excessive, it can approximate as: when A is small, $\log_2 \det(I - A) \simeq Tr(A)$. In particular, if the A's eigenvalues has $\lambda(A) \ll 1$, then:

$$min\ I_{xy}(H,F) \simeq Tr[\bar{D}^2 (I - V^H FF^H V)] \tag{12}$$

2. when SNR is high. i.e. $P_T \gg 1$, then $\bar{D} \simeq I$, there has:

$$min\ I_{xy}(H,F) \simeq \log_2 \det(2I - V^H FF^H V) \tag{13}$$

From Eqs.(12)~(13), if it wants the system capacity loss minimum, the design of codebook F is critical, so next step we take some further discussion. In Eq.(12), the capacity loss minimum is equivalent to maximize $Tr(\bar{D}^2 V^H FF^H V) = \|(V\bar{D})^H F\|_F^2$.

Matrix codebook design guideline: Design a mapping matrix P, make the mutual information loss minimum, i.e.:

$$\max_{P(\bullet)} E\|(V\bar{D})^H P(H)\|_F^2 \tag{14}$$

Where, $F = P(H)$ is the VQ precoding matrix, it is a unitary matrix, $F^H F = I$.

The above problem can be solved by Lloyd algorithm [16]. This paper uses a new designed Lloyd algorithm to improve the VQ method. In our design, "vector" is not only referred to sequence like $\{x_1, x_2, \cdots, x_n\}$, but also can be extended into arbitrary dimension matrix, therefore, the design guidelines for the codebook can be solved by our new vector quantization method.

Now, we give the nearest neighborhood condition (NNC) and centroid condition (CC), codebook design algorithm is as follows:

1. NNC: For an arbitrary codebook $\{F_i; i = 1, 2, \cdots, L\}$, the best divided unit of channel is:

$$\Psi_i = \{H \in \mathbb{C}^{n_r \times n_t} : \|(V\bar{D})^H F_i\|_F^2 \geq \|(V\bar{D})^H F_j\|_F^2, \forall j \neq i\} \quad i, j = 1, 2, \cdots L \tag{15}$$

Where, Ψ_i is the divided unit which belong to the i th element in matrices space $\mathbb{C}^{n_r \times n_t}$.

2. CC: For an arbitrary divided unit Ψ_i, $i = 1, 2, \cdots L$, the best element in this unit is:

$$F_i = arg \max_{F^H F = I} E[\|(V\bar{D})^H F\|_F^2, H \in \Psi_i], i = 1, 2, \cdots L \tag{16}$$

The above two steps are taken iteration according to algorithm requirements, until it calculates the target mapping matrix F, then Eq.(14) will acquire the maximum value. In practical environment, the codebook design is separated from the system, so the optimal channel can be approached by training a large number channel samples, the codebook's quality can be improved, and it needn't increase system complexity.

The codebook has been found now, then we put the designed codebook $\{F_1, F_2, \cdots F_L\}$ into the sender and receiver respectively, next step, the receiver will search for the optimal pre-coding matrix according to the current channel state, i.e. $F = arg \max_{F_i} I_{xy}(H, F_i)$. Then the receiver sends the index value which F in the codebook to the sender (feedback error is not considered). According to this index value, the sender can find the precoding matrix F, and the feedback bit is $B = \log_2 L$.

These steps need to note is that, codebook design already includes the power allocation algorithm, the average power allocation algorithm is used, the transmitting power of each antenna is $p = P_T / n_t$, that is to say, in Fig.3, the precoding matrix F of S is consist of two parts, one is power allocation matrix Λ (diagonal matrix), and the other one is codebook matrix $\bar{V}$ (unitary matrix), the matrix Λ has already known, and this condition is just always taken along when training the precoding matrix. So, is it possible to find a more general codebook structure method, remove the power allocation constraints, and find a codebook which is not related to the transmitting power? Let's discuss it:

1. when SNR is low. i.e. $p \ll 1$ (power on each antenna is very small), $\bar{D} \approx pD^2$, then Eq.(16)'s optimization target is:

$$\max_{P(\bullet)} E \| (V\bar{D})^H P(H) \|_F^2 = \max_{P(\bullet)} E \| H \cdot P(H) \|_F^2 \tag{17}$$

The original optimization target is to maximize the channel H's average gain, but in Eq.(17), at low SNR, the optimization target is to maximize the equivalent channel HF's average gain.

2. when SNR is high. i.e. $p \to \infty$ (power on each antenna is very large), $\bar{D} \to I$, Eq.(16)'s optimization target is:

$$\max_{P(\bullet)} E \| V^H P(H) \|_F^2 \tag{18}$$

Where, $F = P(H)$ is the quantification beamforming matrix, and $F^H F = I$.

When Eqs.(17)~(18) are obtained, according to the previously described, next steps will use our new Lloyd algorithm to acquire the codebook, and calculate the feedback index value, then finally get the precoding matrix F.

IV. Simulation Results

The i.i.d. Rayleigh fading channel is assumed in this section. w.l.o.g., assumption that $\sigma_R^2 = \sigma_D^2 = \sigma^2$, $E_S = E_R = 1$, $[H_{SR}]_{i,j} \sim CN(0, h_{SR}^2)$, $i \in \{1, 2, \cdots, N_S\}$, $j \in \{1, 2, \cdots, N_R\}$, $[G_{RD}]_{i,j} \sim CN(0, g_{RD}^2)$, $[H_{SD}]_{i,j} \sim CN(0, h_{SD}^2)$, $i \in \{1, 2, \cdots, N_R\}$, $j \in \{1, 2, \cdots, N_D\}$, SNR offsets are defined as follows:

$$\rho_{SD} = \frac{h_{SD}^2}{\sigma^2}, \quad \rho_{SR} = \frac{h_{SR}^2}{\sigma^2}, \quad \rho_{RD} = \frac{g_{RD}^2}{\sigma^2}. \tag{19}$$

In a general way, $\rho_{SD} \le \rho_{SR}$, $\rho_{SD} \le \rho_{RD}$, the SNR's relative values of two phrase can be defined as:

$$\Delta_{SR} = \rho_{SR} / \rho_{SD}, \quad \Delta_{RD} = \rho_{RD} / \rho_{SD} \tag{20}$$

Then assumption that $\Delta_{SR} = \Delta_1$, $\Delta_{RD} = \Delta_2$, $i \in \{1, 2, \cdots, M\}$. w.l.o.g., the definition of average SNR is shown in Eq.(19).

As analysis, the average interrupt probability and capacity are respectively used as the criterion to check system reliability and spectral efficiency. Where the average interrupt probability and capacity are defined as follow:

$$P_{out} = \frac{1}{N_S} \sum_{i=1}^{N_S} \Pr(\gamma_i < \gamma_{th}), \gamma_{th} = 1 \tag{21}$$

$$C = \sum_{i=1}^{N_S} E[\log_2(1 + \gamma_i)] \tag{22}$$

First, we evaluate the pre-coding matrix performance under VQ method. The node's antennas are set as: $4 = N_R > N_S = N_D = 2$, channels between antennas content the i.i.d. conditions. In tradition AF relay protocol, D can dispense with MIMO equalizer. In order to comparison, the capacity $C = E[I(H, V)]$ under perfect CSI were normalized, as shown in Fig.4. From the simulation results, we can see that, with the feedback bits increasing, the system capacity is increased, because if the feedback bits is more, the imperfect CSI can be close to the perfect CSI when it is returned to the sender, and the mutual information loss will be little.

It also can be seen from the Fig.4, the system ergodic capacity comparison under different codebook design scheme. At the condition of low SNR [Eq.(17)] and high SNR [Eq.(18)], because the optimization objective functions are different, these two methods both make the system capacity loss minimum, so that the codebook is always consistent with channel's change, and makes the system performance optimal. General VQ method [Eq.(14)] is always better than these two methods, this is because the general VQ method always make the system capacity loss to minimize, it is a generally optimization method, yet Eqs.(17)~(18) are an approximate method, they just can be close to the general VQ method.

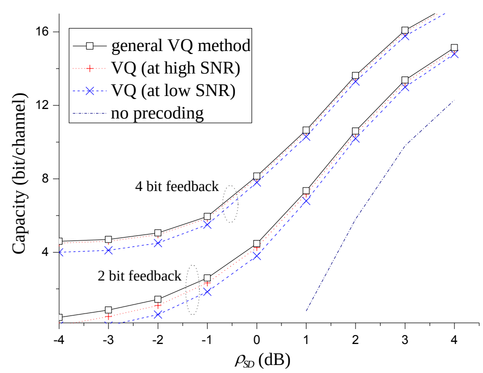

Fig.4 $\Delta_1 = 10dB$, $\Delta_2 = 10dB$, $4 = N_R > N_S = N_D = 2$, capacity comparison

As can be seen from Fig.4, the different number of feedback bits can bring system capacity gain apparently, 4bit codebook feedback compares to 2bit feedback, the system capacity gain is about 4bps/Hz, if the feedback bits are future increased, the system performance will be enhanced more, experiments show that when the number of feedback bits come to 10bit, the channel can be closed to the perfect CSI situation.

The following we simulate the system bit error rate (BER) performance. The antenna configuration and SNR settings are the same as the previous simulation. Modulation is selected as QPSK, the number of feedback bits is 4bit, the rate of sample channel is set 10k bits/s. In the BER-based simulation, different SNR corresponding to the different simulation samples, the lower BER is, the larger required samples, they have the following relationship in mathematics.

$$N_{sample} = \frac{100}{10^b} \tag{23}$$

Where, N_{sample} means the required samples, 10^b means the BER level, b generally is negative integer. Simulation results are as follow:

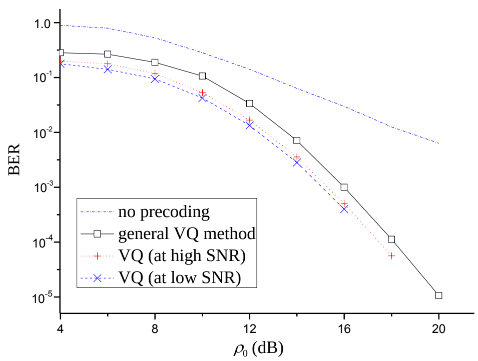

Fig.5 $\Delta_1 = 10dB$, $\Delta_2 = 10dB$, $4 = N_R > N_S = N_D = 2$, bit error rate comparison

Fig.5 shows the BER performance with SNR changes. When the BER is 10^{-2}, the channel matrix which optimized by general VQ method has increased about 4dB (average) gain, when at low SNR and high SNR, the VQ approximate calculation has improved the performance increased 6dB, meanwhile, these two VQ methods are almost the same influenced on BER performance, this is because the system date rate is confirmed, Eqs.(17)~(18) are just only the deformation of channel matrix H , they have no influence on Eq.(23)'s BER level, and the error code of system will be not influenced. However, from the Fig.5, when at low SNR, the VQ approximate calculation is optimal for the BER performance, that is to say, optimization of HF matrix if the best way to improve system's BER performance.

We discuss the transmitting antenna setting influence on system performance. In MIMO relay system, when the receiving antennas number (n_r) is inconsistent with transmitting antennas (n_t), (it is assumed that $n_r \geq n_t$), it is generally to expand antennas operation, in addition to this, we can also do some antenna selection operation, select the same receiving antennas with transmitting antennas, and select the maximum diversity gain antennas in the receiving antennas, which construct the best transmission matrix HF . The antenna selection criteria is critical, different selection criteria may cause channel matrix H 's structure difference.

Generally, the antenna selection criteria can be divided into two kinds: based on system capacity and based on BER. In this simulation, the antenna selection is based on system capacity. The core idea is: the channel matrix which is constituted by the final selection antennas and transmitting antennas can make the system capacity maximum. Assumption that $\tilde{H}_{t\times t} = [h_1, h_2, \cdots, h_t]$, where $h_k = [h_{k_1}, h_{k_2}, \cdots, h_{k_t}]$ is the corresponding vector channel of k th receiving antenna, $1 \leq k_1 \leq k_2 \leq \cdots \leq k_t \leq r$, $(k_1, k_2, \cdots, k_t)$ is the final selection antennas. According to the system mutual information Eq.(9), do some deformation, we can acqiure the antenna selection criteria is:

$$(k_1, k_2, \cdots, k_t) = arg \max_{1\leq k_1 \leq k_2 \leq \cdots \leq k_t \leq r} [\sum_{k=1}^{t} \log_2 (1 + \frac{P_T}{t \cdot \alpha_n^2 \cdot \sigma_n^2})] \tag{24}$$

Where α_n^2 is a coefficient which relative with channel matrix, t is the transmitting antennas.

Eq.(24) is the instantaneous system capacity. We calculate the appropriate number of transmitting antennas t , which make the system capacity maximum, and these antennas are the final selection. The modulation is QPSK, the feedback bits number is 4bit, channel sample rate is 10k bits/s. The fixed channel SNRs are: $\rho_0 = 10dB$, $\Delta_1 = 10dB$, $\Delta_2 = 10dB$, other settings are the same as section 4.1, now we take this paper's VQ method (general VQ method) to simulate system's antenna setting.

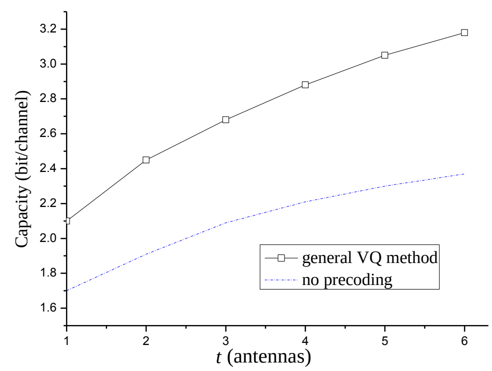

Fig.6 $\rho_0 = 10dB$, $\Delta_1 = 10dB$, $\Delta_2 = 10dB$, capacity comparison with relay number

The system capacity changing with antennas number is shown in Fig.6, the curve is approximate a logarithmic function, which the variable is t . The more relay nodes number (the greater number of transmitting antennas), the greater space freedom degree of distributed spatial precoding, so the difference will become more and more larger. It also can be seen from the figure, comparing with no precoding system, the VQ method is more obvious on antenna diversity gain performance. When $t = 4$, system capacity gain is about 0.8bps/Hz, and this increasing trend becomes more and more apparently, when $t = 6$, the difference between two curves is about 1bps/Hz. This also shows that VQ method has the fast adaptive ability for antenna arrays changing, to improve the system capacity gain.

V. Conclusion

In this paper, a forward pass multi-antenna single-relay system precoding scheme is researched. In general way, because the sender is unable to obtain full CSI, paper has focus on imperfect CSI conditions, and research relay system precoding.

The limited feedback idea is used, from the relay system equivalent channel matrix H, construct a power allocation diagonal matrix and a codebook matrix. In order to decrease feedback bits, a new vector quantization method is used to construct the codebook matrix, then to design the virtual MIMO precoding matrix. Meanwhile, the new VQ codebook design method is generally related with transmitting power, the nodes will work under different transmitting power, so it needs many codebooks, which to some extent, increase the training codebook complexity. Therefore, the future research can be classified on the relay channel, classify the channel into some different types under different SNR, for each type, we use one codebook, make it nothing to do with the transmitting power.

ACKNOWLEDGMENT

This work was supported by the National Key Laboratory Opening Task (KF2N2014W01-002), and Fundamental Research Funds for the Central Universities (2015ZCQ-GX-04). The authors would like to appreciate the anonymous reviewers for their constructive comments.

REFERENCES

[1] Tao Xiaofeng, Xu Xiaodong, Cui Qimei, “An overview of cooperative communications,” *IEEE Communications Magazine*, Vol. 50, No. 6, pp. 65-71, 2012.

[2] Yau Kok-Lim Alvin, Goh Hock Guan, Chieng David, Kwong Kae Hsiang, “Application of reinforcement learning to wireless sensor networks: models and algorithms,” *Computing*, Vol. 97, No. 11, pp. 1045-1075, 2015.

[3] Song S.H., Hasna, M.O., Letaief, K.B., “Prior Zero Forcing for Cognitive Relaying,” *IEEE Transactions on Wireless Communications*, Vol. 12, No. 2, pp. 938-947, 2013.

[4] Muzi F., Bayasgalan Z., “A digital protection procedure for smart grid reconfiguration after faults,” *International Journal of Circuits, Systems and Signal Processing*, Vol. 9, pp. 153-159, 2015.

[5] Kijima Hitoshi, Ochi Koji, “Proposal of double voltage transmission line pulse generator using four coaxial cables,” *International Journal of Circuits, Systems and Signal Processing*, Vol. 8, pp. 30-37, 2014.

[6] Wang Rui, Tao Meixia, Xiang Zhengzheng, “Nonlinear precoding design for MIMO amplify-and-forward two-way relay systems,” *IEEE Transactions on Vehicular Technology*, Vol. 61, No. 9, pp. 3984-3995, 2012.

[7] Bouderbala R., Bentarzi H., Ouadi A., “Digital differential relay reliability enhancement of power transformer,” *International Journal of Circuits, Systems and Signal Processing*, Vol. 5, No. 3, pp. 263-270, 2011.

[8] Maddah-Ali M. A., Sadrabadi M. A. Khandani A. K., “Broadcast in MIMO systems based on a generalized QR decomposition: Signaling and performance analysis,” *IEEE Transactions on Information Theory*, Vol. 54, No. 3, pp. 1124-1138, 2008.

[9] Razavi S. Morteza, Ratnarajah Tharmalingam, “Channel inversion and regularization revisited,” *Signal Processing*, Vol. 121, No. 4, pp. 70-80, 2016.

[10] Chua Wee Seng, Yuen Chau, Guan Yong Liang, et al., “Robust multi-antenna multi-user precoding based on generalized multi-unitary decomposition with partial CSI feedback,” *IEEE Transactions on Vehicular Technology*, Vol. 62, No. 2, pp. 596-605, 2013.

[11] Tang Ming-Fu, Su Borching, “Downlink Precoding for Multiple Users in FDD Massive MIMO Without CSI Feedback,” *Journal of Signal Processing Systems*, Vol. 83, No. 2, pp. 151-163, 2016.

[12] Chen Xing, Zhang Jian, Lu Jinlong, et al., “Feed-forward digital phase compensation for long-distance precise frequency dissemination via fiber network,” *Optics Letters*, Vol. 40, No. 3, pp. 371-374, 2015.

[13] Luo Zhen, Zhang Lin, Leung Shu-hung, “Statistically robust precoder design over correlated Rician MIMO channels,” *Signal Processing*, Vol. 102, No. 9, pp. 177-187, 2014.

[14] Noori Moslem, Lampe Lutz, “Multi-way relaying for cooperative indoor power line communications,” *IET Communications*, Vol. 10, No. 1, pp. 72-80, 2016.

[15] Ni Weiheng, Dong Xiaodai, “Hybrid block diagonalization for massive multiuser MIMO systems,” *IEEE Transactions on Communications*, Vol. 64, No. 1, pp. 201-211, 2016.

[16] T. Strohmer and R. W. J. Heath, “Grassmannian frames with applications to coding and communications,” *Applied and computational Harmonic Analysis*, Vol. 14, No. 3, pp. 257-275, 2003.

[17] Katsavounidis Ioannis, Kuo C.-C.Jay, Zhang Zhen, “New initialization technique for generalized Lloyd iteration,” *IEEE Signal Processing Letters*, Vol. 1, No. 10, pp. 144-146, 1994.

[18] Yuen Chau, Hochwald Bertrand M., “Achieving near-capacity at low SNR on a multiple-antenna multiple-user channel,” *IEEE Transactions on Communications*, Vol. 57, No. 1, pp. 69-74, 2009.

[19] Chua Wee Seng, Yuen Chau, Chin Francois, “A continuous vector-perturbation for multi-antenna multi-user communication,” *IEEE Vehicular Technology Conference, VTC2007-Spring*, pp. 1806-1810, 2007.

[20] R. A. Horn and C. R. Johnson, *Matrix Analysis [M]*. 1985, Cambridge, U.K.: Cambridge Univ. Press.

[21] G. H. Golub, C. F. Van Loan, *Matrix Computations [M]*. 1996, Baltimore, MD: Johns Hopkins Univ. Press.

Chaoyi Zhang born in December 1985, received his Bachelor's degree in Measurement control technology and instruments from Beijing University of Posts and Telecommunications, Beijing, China, at 2003~2007, received his Master and Ph.D degree in Communication and Information System from Beijing University of Posts and Telecommunications, Beijing, China, at 2007~2012. Since July of 2012 he worked in National Agricultural Intelligent Equipment Technology Research Center. His research interests include cooperative communication, relay transmission, signal processing, communication theory, and he has great interest in 5G technologies.

Ruirui Zhang received his Bachelor and master degree in Beijing Jiaotong University, Beijing, China, at 2007, now he is senior engineer in National Agricultural Intelligent Equipment Technology Research Center. He is interested in researching in Wireless sensor network positioning optimization, signal processing, agricultural information technology.

Yan Yao received her Bachelor's degree in Machinery from Beijing University of Posts and Telecommunications, Beijing, China, at 1987, received her engineering master degree in mechanical engineering and automation from Beijing University of Posts and Telecommunications, Beijing, China, at 2008, now she is senior engineer in Beijing University of Posts and Telecommunications. She is interested in researching in Wireless sensor network positioning optimization, Ad Hoc wireless network, high-speed network traffic control and performance analysis, GPS locating, HD video conferencing.