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Adaptive Vector Quantization in SVD MIMO System Backward Link with Limited Number of Active Subchannels

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Abstract: This paper presents combination of Channel Optimised Vector Quantization based on LBG algorithm and subchannel power allocation for MIMO systems with Singular Value Decomposition and limited number of active subchannels. Proposed algorithm is designed to enable maximal throughput with bit error rate bellow some target level in case of backward channel capacity limitation. Presence of errors effect in backward channel is also considered.

Keywords: MIMO systems, Space-time coding, Vector quantization.

1 Introduction

Multiple Input Multiple Output (MIMO) represents technology that can highly increase wireless system capacity. It is well known that optimal MIMO system performances can be achieved if system is realized according to Singular Value Decomposition (SVD) principle or channel decomposition to several subchannels. In our previous work [3], system with adaptive Quadrature Amplitude Modulation (QAM) modulation applied in subchannels is proposed (figure 1).

Transmission with throughput that is approaching QAM theoretic limits is obtained in this way. Further improvement can be reached if error-control coding (ECC) techniques are implemented. For successful implementation, transmitter has to be provided with channel state information (CSI). If channel state is known both at transmitter and receiver side, this information is used for adaptive capacity improvement methods.

Reverse channel imperfections represent basic limitations in practical systems. Beside the delay, that represents the main problem (and can be highly reduced with adaptive linear prediction techniques); one of basic restrictions is limited backward link capacity also. It is assumed that channel matrix changes in every transmission frame, and with every change, $n_R n_T$ estimated complex coefficients have to be transmitted through the feedback channel. Information that is sent through the digital reverse link has to be

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converted from vectors to bits in such a way that number of transmitted bits per one vector has to be minimized and damage level put below the certain value.

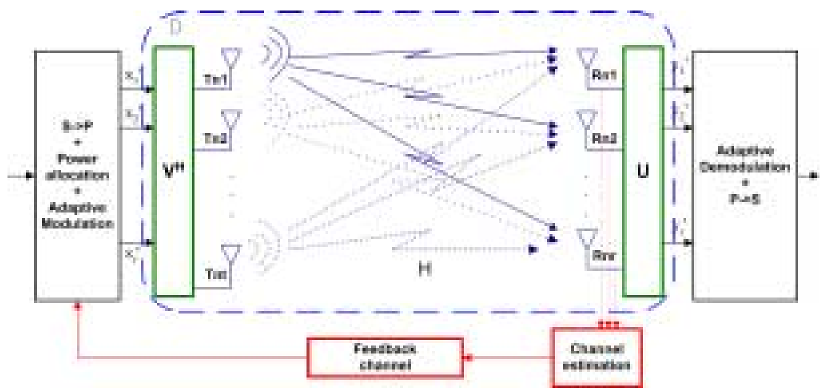

Fig. 1 - *Adaptive MIMO system with SVD.*

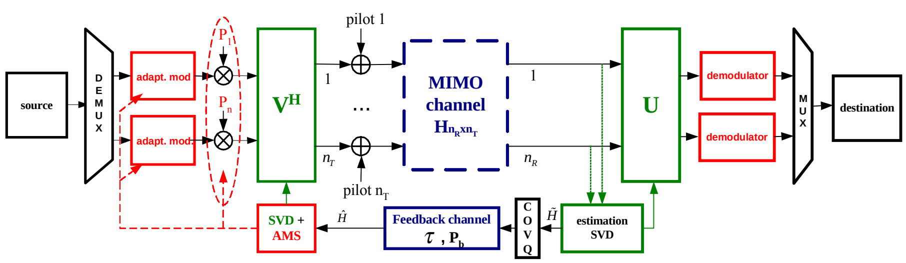

Fig. 2 - *Block diagram of SVD MIMO system with adaptive modulation, optimal power allocation, quantization in feedback channel*

2 Vector Quantization in MIMO System

There are several methods for representation of CSI in digital format. In UMTS system c*lose-loop* mode [4], with one antenna at receiver and two antennas at transmitter (n_R=1, n_T=2), problem is simplified to with phase difference quantization of channel matrix coefficients.

It is clear that with this approach some complexity savings can be obtained only in low-order systems. In the case of SVD system, all coefficients have to be quantized. One of the best methods for signal quantization with any *k*-dimensional distribution is Channel Optimised Vector Quantization (COVQ). This method is based on damage level minimization. If number of code words is a priory known, it is possible to find set of code words (*codebook*) and to determine appropriate quantizatation regions, with goal to minimize information damage (mean square error),

$$D_{ave} = \frac{1}{Mk}\sum_{m=1}^{M}\left\| x_m - Q(x_m) \right\|^2 \rightarrow \min .$$

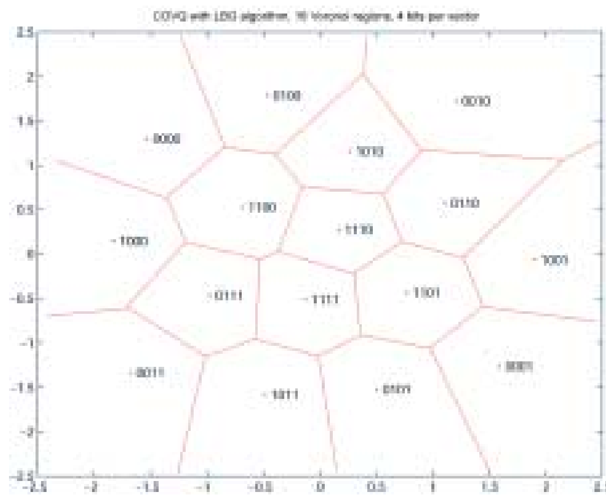

Fig. 3a - *N=16, Voronoi regions for two-dimensional Gaussian PDF.*

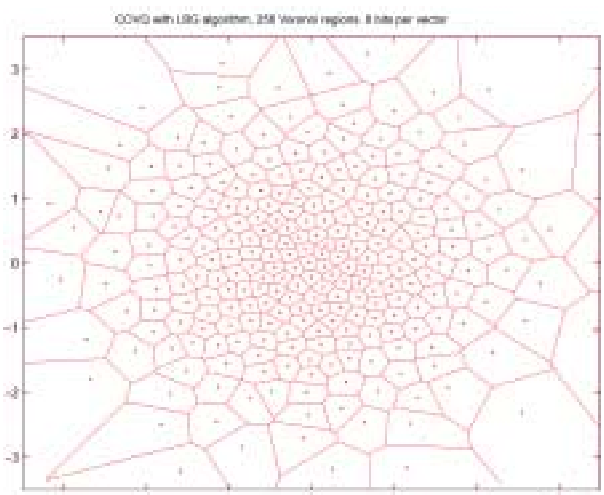

Fig. 3b - *N=256, Voronoi regions*, *two-dimensional Gaussian PDF*.

In this method, training sequence is used to determine quantizer parameters (code-word set and quantization regions) that are fixed during the further work. Quantizer doesn't have to "know" *a-priori* source signal statistical properties (probability density function…). Same quantizer can work very well for a lot of source signals (with different PDF-s), and for un-stationary signals too.

Quantizer parameters are determined with appropriate algorithm that satisfies optimality conditions – nearest neighbour and centrality condition. In addition, because of limited capacity, is not desirable to use error control codes in reverse channel.

LBG algorithm [5] is one of the most efficient quantization algorithms. It results in very fast quantization vectors and code words creation. In addition, if every of N code vectors can be represented with set of $\log_2 N$ bits, it can be shown that Hamming distance between neighbouring code words distance is minimal, similar to Gray mapping in constellations. This property of LBG is illustrated in figure 3a, where code words are represented for the case of two-dimensional Gaussian distribution and $N = 16$ regions. Figure 3b shows very clear that regions dimensions highly depend on PDF and number of quantization regions highly affects quantization error.

Channel optimised vector quantization with LBG algorithm can be applied for the channel matrix coefficients transmission through adaptive system backward channel. Transmitted digital signal represents corresponding binary code vectors representation. On the receiver side, coefficient regeneration with lower and higher accuracy (depending of quantization order) is performed.

Because of quantization effect illustration, performance estimation for 2x2 MIMO system for various quantization regions number is analysed. Proposed system uses only the best subchannel (*beam forming* method) with BPSK modulation. Results are presented in figure 4. Near-ideal performances are achieved for $N = 64$ quantization regions (codeword length $k = 6$). This way, even for modest reverse link capacity, channel state matrix elements can be delivered to the transmitter with great accuracy. It can be shown that rough quantization with only four regions results in lower system performances than open-loop Alamouti space-time code! Quantization with 16 regions corresponding to UTRA/FDD system close-loop mode 2, but in this case phase and amplitude quantization is performed simultaneously.

Of course, greater regions number results in higher throughput in backward link. For example, for N =32 regions, it is necessary to transmit $2x2x\log_2 32 = 20$ bits per one time transmission interval (TTI).

Also, it is clear that in this example *beam forming* system with un-coded BPSK reaches constant spectral efficiency of 1b/s/Hz and bit error probability BER=10^{-3} can be reached for signal to noise ratio SNR >5dB. For greater SNR values, bit error probability has lower value than necessary and in that case higher order modulation can be used, but greater sensitivity from quantization refinement level is increased too.

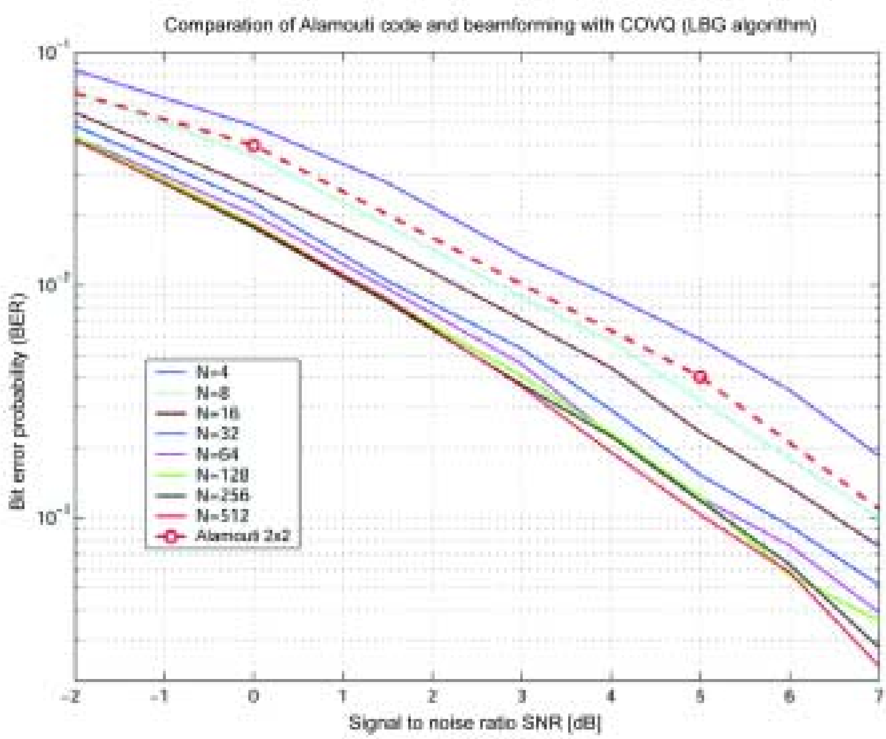

Fig. 4 - *Performance of comparation of close-loop system with LBG and Alamouti close-loop system.*

3 Used Constellations and Power Allocation

Transmitter power allocation strategy depends on of channel state information. Allocation on subchannels is performed according to *water-filling* principle, applied only in active subchannels.

For realistic signal to noise ratios and typical MIMO system dimensions (up to 4x4, what results is acceptable space correlation level) best results can be achieved if constellations up to 64-QAM [3] are used. That is considered optimal in some already realized MIMO systems (for instance HSDPA [6], Lucent BLAST system, METRA and I-METRA proposed systems).

If quantization is performed with limited number of regions ortogonalisation degrade and partial interference from other subchannels appears. Transmission with 64-QAM isn't reliable any more and degradation appears for high signal to noise ratios, like in figure 5. In further analysis, we will consider 16-QAM as the highest-level modulation used.

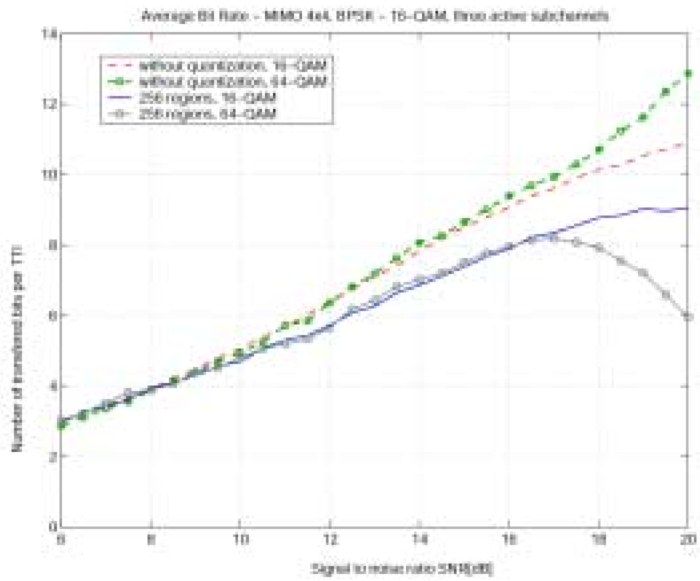

Fig. 5 - *Quantization effect for various high-level modulations.*

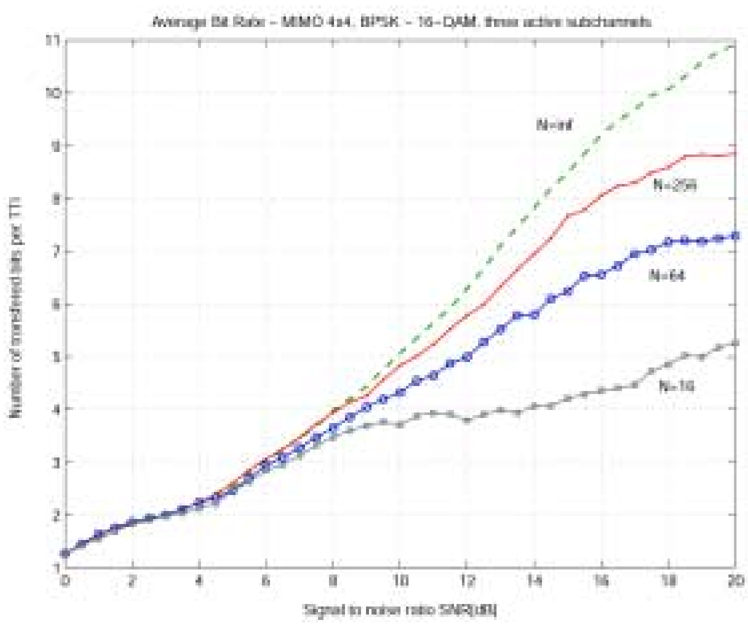

Fig. 6 - *Quantization levels number effect.*

Spectral efficiency in case of LBG quantization with N =16, N =64 and N =256 regions is shown at figure 6. For realistic signal to noise ratios, quantization with less then 256 regions results in significant degradation. This can be explained with great channel coefficients estimation inaccuracy, which results in rough orthogonalization and very high interference level among subchannels.

When modulation schemes set (BPSK, QPSK, 8-PSK and 16-QAM) and number of quantization regions (N =256) are chosen, influence of active subchannels number on spectral efficiency can be determinate. Analysis shows (fig 7) that three strongest subchannels use doesn't degrade efficiency at all! This is the consequence of fact that transmission in the weakest subchannel became possible only for very low noise level (SNR >15 dB). As quantization always results in some interference level that dictates transmission quality, this subchannel is activated very rarely, and always with BPSK.
For two active subchannels, degradation occurs for SNR >12 dB. Even for high signal to noise ratios ($SNR \geq 20$dB) this system spectral efficiency outperforms twice efficiency of system that use only the strongest subchannel (*beam forming*).

It can be concluded that systems with two or three active subchannels have much better efficiency than *beam forming* system and doesn't have worse efficiency compared to optimal SVD system.

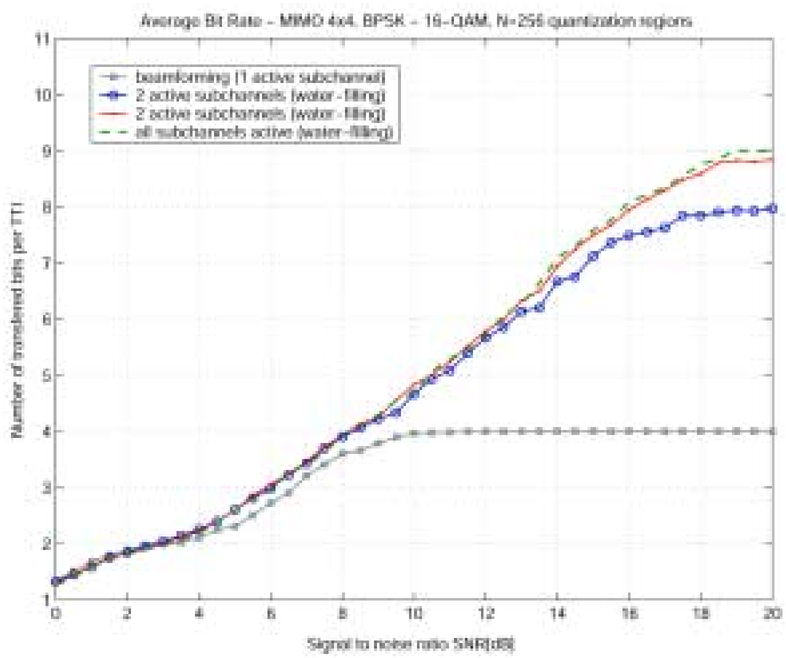

Fig. 7 - *Spectral efficiency for different number of active subchannels.*

4 Feedback Link Optimisation

It is already mentioned that full MIMO channel orthogonalization can be achieved using the singular value decomposition,

$$H = UDV^H,$$

where U and V are unitary matrices, and diagonal entries of D are nonnegative square roots of matrix HH^H eigenvalues so with introduction of following transformations, it can be written:

$$y' = U^H y,\ \ x' = V^H x,\ \ n' = U^H n \ \Rightarrow y' = Dx' + n'.$$

Also, it is known that *beam forming* system transmitter simply scale symbols from data flow x with coefficients described by a vector w,

$$x' = Hwx + n = H_{ekv}x + n.$$

Vector w is chosen to maximize scalar: $w^H H^H Hw = \lambda_{\max} I_{nR}$ so transmission through the strongest subchannel can be achieved if weighted coefficients vector w is the eigenvector of matrix HH^H that correspond to its greatest eigenvalue. Therefore, it isn't necessary to transfer all matrix $H_{n_R x n_T}$ coefficients on the transmitter side. It is enough to transfer n_T elements of vector w, or matrix V first column.

It is easy to show that transmission through two strongest subchannels requires knowledge about two vectors w_1 and w_2 (both with dimensions $n_T x1$), or two eigenvectors that corresponding to the greatest matrix HH^H eigenvalues. In fact it is first two matrix V columns, used for orthogonalization on the transmitter side. Same method can be repeated for transmition through three subchannels.

It is clear that transmitter and receiver filter (V and U), for all of these cases, can be realized as combinatory logic circuits, like on the figure 8. This figure also illustrate concept of "active subchannels" as two subchannels that are used for transmission (in this example).

If there is more than one active subchannel, it is also necessary to transfer eigenvalues, because they are used in *water filling* power optimisation procedure. Nevertheless, this is scalar value and compared with n_T times more complex coefficients, this transmission isn't critical. Besides, even if eigenvalues aren't known at the transmitter side, in the case of symmetric system ($n_R = n_T$) uniform power allocation on active subchannels doesn't lead to severe efficiency degradation, comparing to optimal procedure.

It is clear that required feedback link capacity mostly depends on system order, active subchannels number and quantization regions number. During the Time Transmition Interval (TTI) of 0.67ms, required capacity for different MIMO system parameters is shown in Table 1.

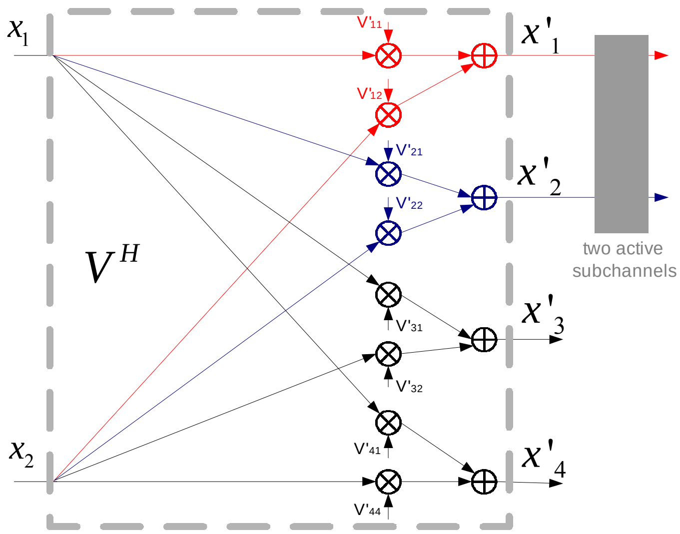

Fig 8 - *Structure of orthogonalization filter on transmitter side.*

Table 1: *Required feedback link capacity for COVQ with LBG, TTI=0.67ms.*

System order / number of active subchannels	Quantization regions number	Required capacity
1x1 /1	64	9 kb/s
1x1 /1	256	12 kb/s
2x2 /2	256	24 kb/s
2x2 /1	256	12 kb/s
4x4 /4	256	192 kb/s
4x4 /3	256	144 kb/s
4x4 /2	256	96 kb/s
4x4 /1	256	48 kb/s
4x4/ 3	512	162 kb/s

It is easy to conclude that optimal solution represents system with great number of quantization levels, large enough to perform quality orthogonalization. It is very important to "turn off" some of the worst subchannels that practically don't degrade efficiency but highly reduce feedback channel throughput. Of course, central part of system block diagram is now modified, like in figure 9. In changed system, there is transfer of some matrix V columns and eigenvalues instead of channel matrix. Such signal is transferred through LBG quantizer and feedback channel. On the transmitter side, matrix V columns are used for orthogonalization and eigenvalues are used for modulation schemes selection and power allocation.

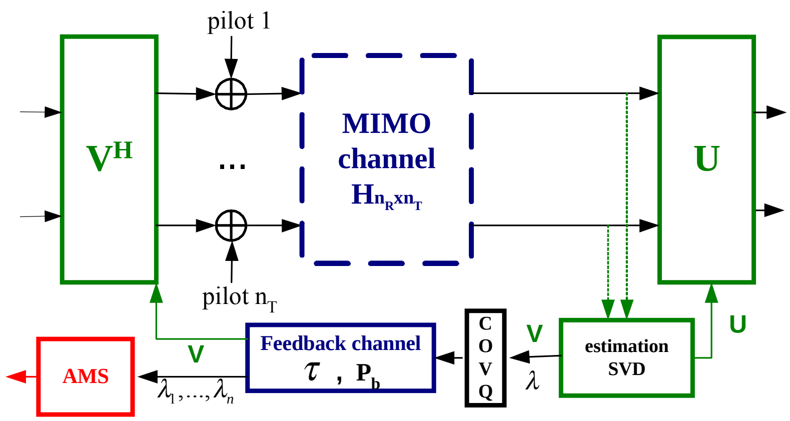

Fig. 9 - *Feedback link modification*.

5 Conclusion

In this paper, we have analysed MIMO system with singular value decomposition that doesn't use all available subchannels for transmission One channel state information quantization method is considered, with goal to enable simpler transmission through feedback channel.

Simulations show that LBG algorithm represents good base for quantization in feedback channel. Besides the, optimal quantization regions disposition, this algorithm ensure optimal code vectors choice, in sense of Hamming distances minimization among neighbouring code vectors. That leads to minimal bit error probability for fixed number of wrong received symbols. This is very important, because it isn't appropriate to use ECC in feedback channel. Besides, high adaptation level in algorithm gives possibility to trace fading parameters during the time.

Feedback scheme modification provides savings in number of complex mathematical operations, because decomposition repeating on transmitter side is avoided. Also, less data transmition amount through backward channel is provided. Combination of these techniques can highly reduce required feedback channel capacity.

5 References

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