Linear Scalable Dispersion Codes: Signal Design and Performance Analysis

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***Abstract*— Using Tarokhs criteria for space-time codes [1] we analyze the design of the Linear Scalable Dispersion (LSD) codes [2]. These codes are designed to utilize large numbers of transmit antennas, to exploit high diversity factors and to trade spatial diversity gain for spatial multiplexing gain in a very flexible way. We investigate the diversity and coding gain for Rayleigh fading and show in particular that these codes are able to achieve full spatial and temporal diversity even in combination with spatial multiplexing.**

I. Introduction

The demand for high data rates at different quality-of-service (QoS) requirements to support broadband data access will increase in future wireless communication systems. Fading caused by destructive interference of multipaths in the wireless propagation medium affects the average reliability of a communication link for a given signal power. However, using multiple transmit and/or receive antennas it is possible to get high data rates on a rich scattering wireless channel. There are two basic coding methods for this purpose, namely space-time coding to improve *link reliability* and spatial multiplexing to increase *spectral efficiency*.

Space-time codes combat the fading effects by utilizing the *diversity* of the communication channel. Such methods aim to achieve *transmit (Tx) diversity* without channel state information at the transmitter. In the last few years space-time coding methods have enjoyed a tremendous amount of attention and some important representatives like space-time block codes based on orthogonal designs [3], [4], space-time trellis codes [1] were developed. In [1] Tarokh *et al.* developed design criteria for space-time codes over Rayleigh and Ricean fading channels.

The use of multiple antennas at the transmitter and the receiver makes an increase in channel capacity possible. In an uncorrelated Rayleigh fading environment the capacity grows linearly as the number of transmit and receive antennas grow simultaneously [5], [6]. This dramatic increase in capacity is possible without an increase of the bandwidth.

Spatial multiplexing exploits this offered capacity by breaking up the data stream into parallel substreams which are then transmitted simultaneously on individual antennas [7]. V-BLAST (Vertical Bell Labs Layered Space-Time) is a practical scheme that uses spatial multiplexing [8]. This scheme is not designed to exploit additional diversity, if there are more transmit than receive antennas.

In [9] a wide class of space-time codes is presented called *linear dispersion (LD) codes*. Every linear block code can be described as a LD code, i.e. these codes include e.g. the orthogonal space-time block codes and the BLAST system as special cases.

In [10] the ST-LCP codes are proposed, a space-time (ST) coding scheme using linear constellation precoding (LCP) in combination with an Tx antenna array to achieve Tx diversity (e.g. by Tx antenna switching).

Another coding scheme that allows a combination of spatial multiplexing and diversity methods is proposed in [11].

If it is better to use spatial multiplexing or transmit diversity methods, depends on a number of parameters, such as a demanded link reliability, a demanded data rate, channel conditions (correlated or uncorrelated fading, Rayleigh or Ricean fading), etc. So it is desirable to use a coding scheme that allows a flexible tradeoff between spatial multiplexing and transmit diversity [12].

The linear scalable dispersion (LSD) codes proposed in [2] are designed as non-orthogonal, linear high rate codes that are in particular very scalable and adaptive; they allow a rich tradeoff between spatial diversity and spatial multiplexing and are able to utilize the potential of rich arrays (antenna arrays with a large number of antennas) with reasonable (and scalable) decoding complexity. This tradeoff is possible due to the structure of this coding scheme. Simulation results show remarkable performance for Rayleigh and Ricean flat fading [13] as well as in combination with OFDM [14] for frequency selective fading (space-frequency coding).

In this paper we investigate the diversity and coding gain of the LSD codes in comparison to the coding schemes presented in [9], [10] and [11] and show in particular that the LSD codes are able to achieve full spatial and temporal diversity even in combination with spatial multiplexing.

II. Linear Scalable Dispersion Codes

In the following we will give a brief description of the linear scalable dispersion (LSD) codes proposed in [2].

A time series representation of the coding scheme is depicted in Fig. 1. The LSD codes consist of two concatenated but (due to the reshaping block) decoupled linear block codes, the *time variant inner code* and the *time invariant outer code*, given by matrices $\mathbf{C}_\nu$ and $\mathbf{R}$ respectively. No a priori channel knowledge is required at the transmitter; we assume perfect

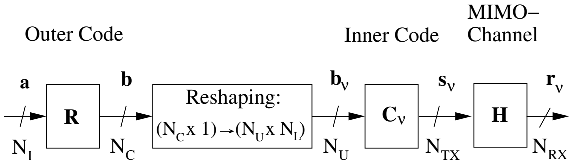

Fig. 1. Symbol discrete model of the encoding scheme

channel state information (CSI) at the receiver (Rx), that uses N_{RX} receive antennas.

The input symbol vector $\mathbf{a}$, consisting of N_I information symbols, is multiplied with the $N_C \times N_I$ outer code matrix $\mathbf{R}$ to form the transmit symbol vector $\mathbf{b}$. The dimensions of the code matrix determine the code rate to $r_c = \frac{N_I}{N_C}$. Thereafter the transmit symbol vector $\mathbf{b}$ of dimension $N_C \times 1$ is reshaped into a $N_U \times N_L$ matrix. The columns of this matrix are the consecutive $N_L = \frac{N_C}{N_U}$ input vectors $\mathbf{b}_\nu$ of the linear time-variant inner code $\mathbf{C}_\nu$, whereas ν is the time index.

The system transmits $N_U \leq \mathrm{rank}\,(\mathbf{H})$ symbols in one time step ν using the N_{TX} transmit antennas; $\mathbf{H}$ is the $N_{RX} \times N_{TX}$ MIMO channel matrix. We refer to N_U as the number of *spatial subchannels* to be used for spatial multiplexing. For $N_U < \mathrm{rank}\,(\mathbf{H})$ the remaining spatial dimensions can be used by the code to achieve an additional diversity gain.

The inner code $\mathbf{C}_\nu$ is adapted to the configurations of the MIMO system (N_{TX}, N_{RX}, N_U) and the channel statistics (Rayleigh or Ricean fading). Pure TX diversity $(N_U = 1)$, spatial multiplexing $(N_U = \mathrm{rank}\,(\mathbf{H}))$ or a combination of both $(1 < N_U < \mathrm{rank}\,(\mathbf{H}))$ are possible configurations of the inner code. The inner code is optimized with respect to the outage capacity of the channel conceived by the outer code. In [2] efficient code matrices are presented for pure TX diversity and for joint TX diversity and spatial multiplexing. Using spatial multiplexing an efficient choice of $\mathbf{C}_\nu$ is given by

$$\mathbf{C}_\nu = \mathrm{diag}(\mathbf{c}_\nu) \cdot \mathbf{M} \tag{1}$$

The N_L vectors $\mathbf{c}_\nu$ are the first N_L columns of a $N_{TX} \times N_C$ Fourier matrix $\mathbf{F}$ with the elements given by

$$\mathbf{F}[n, m] = \frac{1}{\sqrt{N_C}} \cdot e^{-j \cdot 2\pi (n-1)(m-1)/N_C} \tag{2}$$

The time invariant matrix $\mathbf{M}$ is a $N_{TX} \times N_U$ unitary matrix based on the impulse response of a cyclic chirp filter. Such a chirp matrix is complex and unitary. The columns are found by cyclic shifting of the first column $\mathbf{M}[:, 1]$, that is given by the Fourier transform of the vector $\mathbf{m}$

$$\mathbf{m}[i] = e^{j \cdot 2\pi b \cdot (i-1)^2 / N_{TX}^2} \tag{3}$$

The optimization of the parameter b and therefore the determination of the elements of $\mathbf{M}$ is described in [2]. The adaptation to a different number N_U of spatial subchannels can simply be done by adding/deleting columns of $\mathbf{M}$.

In the case of pure transmit diversity ($N_U = 1$) one good set of inner coding vectors is given by first N_{TX} columns of the Fourier matrix $\mathbf{F}$. Another simple choice for a time variant inner code are the columns of a identity matrix $\mathbf{I}$: the TX antennas are switched. Therefore the equivalent fading coefficients are time-variant if the channel is variant in the spatial dimension.

The outer code $\mathbf{R}$ is optimized for diversity performance [2] and achieves a high diversity gain and an excellent performance in a fading environment even at code rate 1 [13]. The considered cost function is the maximal fading averaged pairwise error probability. As described in [2] the cyclic matrix $\mathbf{R}$ of dimension $N_I \times N_C$ is unitary. The columns of $\mathbf{R}$ are also samples of the cyclic impulse response of a chirp filter, given by cyclic shifting of the first column $\mathbf{R}[:, 1]$, that is given by the Fourier transform of the vector $\mathbf{r}$

$$\mathbf{r}[i] = e^{j \cdot 2\pi d \cdot (i-1)^2 / N_C^2}. \tag{4}$$

with an optimization of the parameter d [2].

Due to this form of code concatenation the diversity performance optimization and channel conditioning (adaptation to the number of TX and RX antennas, pure TX diversity, pure spatial multiplexing, joint spatial multiplexing and TX diversity, number of spatial subchannels) are decoupled.

III. Diversity and coding gain

A. *Coding for pure diversity, no spatial multiplexing*

Pure diversity means $N_U = 1$, $N_L = N_C$, the matrix $\mathbf{C}_\nu$ and the vector $\mathbf{b}_\nu$ become a column vector $\mathbf{c}_\nu$ and a scalar b_ν, respectively. To transmit the vector $\mathbf{b} = \mathbf{R}\mathbf{a}$ the code matrix $\mathbf{S}$ is given by:

$$\begin{aligned} [\mathbf{s}_{\nu=1}, \mathbf{s}_2, ..., \mathbf{s}_{\nu=N_C}] &= [\mathbf{c}_{\nu=1}, \mathbf{c}_2, ..., \mathbf{c}_{N_C}] \cdot \mathrm{diag}(\mathbf{b}) \\ \mathbf{S} &= \mathbf{C}_{Div} \cdot \mathrm{diag}(\mathbf{b}) \end{aligned} \tag{5}$$

The $N_L = N_C$ vectors $\mathbf{s}_\nu$ $(\nu = 1, 2, ..., N_L)$ build the $N_{TX} \times N_C$ matrix $\mathbf{S}$, the N_C vectors $\mathbf{c}_\nu$ the $N_{TX} \times N_C$ matrix $\mathbf{C}_{Div}$. The matrix diag($\mathbf{b}$) is a diagonal $N_C \times N_C$ matrix with the N_C elements of $\mathbf{b}$ on the main diagonal.

According to [1] for a quasi-static flat i.i.d. Rayleigh fading channel $\mathbf{H}$ an upper bound on the average pairwise error probability (averaged over channel statistics) for two code matrices $\mathbf{S}^{(1)}$ and $\mathbf{S}^{(2)}$ at high SNR is given by

$$P(\mathbf{S}^{(1)} \to \mathbf{S}^{(2)}) \leq \left(\prod_{i=1}^{r} \lambda_i \right)^{-N_{RX}} \cdot \left(\frac{\rho}{4 N_{TX}} \right)^{-r \cdot N_{RX}} \tag{6}$$

where ρ is the mean SNR at each receive antenna and r is the rank of the matrix $\mathbf{A} = (\mathbf{S}^{(1)} - \mathbf{S}^{(2)})(\mathbf{S}^{(1)} - \mathbf{S}^{(2)})^H$. λ_i denotes the i-th nonzero eigenvalue of $\mathbf{A}$. The matrix $\mathbf{B} = (\mathbf{S}^{(1)} - \mathbf{S}^{(2)})$ has the same rank as $\mathbf{A}$.

The *coding gain* (Tarokhs determinant criterion [1]) is given by the term

$$G = \left(\prod_{i=1}^{r} \lambda_i \right)^{\frac{1}{r}} \tag{7}$$

.

From (6) follows that the *diversity gain* is given by $r \cdot N_{RX}$ (Tarokhs rank criterion). Because the maximum rank of the $N_{TX} \times N_C$ matrix $\mathbf{B}$ is $\min(N_{TX}, N_C)$ and because

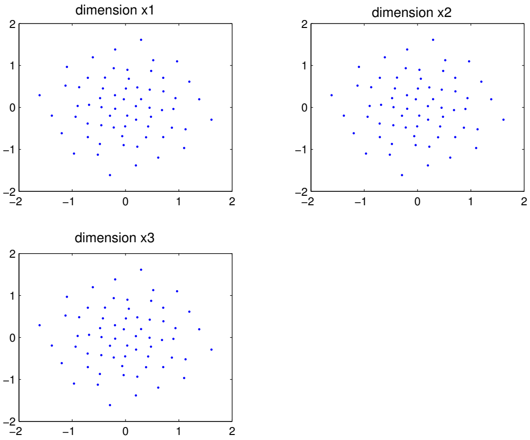

Fig. 2. Outer code: chirp matrix; all 64 coded vectors for block length $N_C = N_I = 3$ and 4QAM

$N_C \geq N_{TX}$ (LSD code design [2]) the maximum diversity gain is $N_{TX} \cdot N_{RX}$.

$$\begin{aligned} \mathbf{B} &= \mathbf{C}_{Div} \left(\text{diag}(\mathbf{b}^{(1)}) - \text{diag}(\mathbf{b}^{(2)}) \right) \\ &= \mathbf{C}_{Div} \left(\text{diag}(\mathbf{Ra}^{(1)}) - \text{diag}(\mathbf{Ra}^{(2)}) \right) \qquad (8) \\ &= \mathbf{C}_{Div} \cdot \text{diag}(\mathbf{R} \cdot \Delta\mathbf{a}^{(21)}) \qquad (9) \end{aligned}$$

According to section II the $N_{TX} \times N_C$ matrix $\mathbf{C}_{Div}$ is given by a $N_{TX} \times N_C$ fourier matrix $\mathbf{F}$. This means that $\mathbf{C}_{Div}$ has maximum rank $r = N_{TX}$.

As described in section II the outer code matrix $\mathbf{R}$ is a unitary matrix based on the cyclic impulse response of a chirp filter and found by optimization. Because of the construction of matrix $\mathbf{R}$ the vector $\mathbf{R} \cdot \Delta\mathbf{a}^{(21)} = \mathbf{R}(\mathbf{a}^{(1)} - \mathbf{a}^{(2)})$ contains no zeros for $\mathbf{a}^{(1)} \neq \mathbf{a}^{(2)}$, i.e. the $N_C \times N_C$ matrix $\text{diag}(\mathbf{R} \cdot \Delta\mathbf{a}^{(21)})$ is nonsingular. This is an interesting feature of the chirp matrix $\mathbf{R}$. As an example consider block length $N_C = N_I = 3$ and 4QAM input symbol vectors $\mathbf{a}_i$; we can distinguish $64 = 4^{N_C}$ different vectors $\mathbf{a}_i$ of dimension 3×1. Fig. 2 shows for all 64 coded vectors $\mathbf{b}_i = \mathbf{Ra}_i$ the values of $\mathbf{b}_i$ in the dimensions x_1, x_2, x_3. There are 64 different values in every dimension; so, the vector $\mathbf{R} \cdot \Delta\mathbf{a}^{(21)}$ does not contain zeros; the same can be found for all block lengths N_C and other symbol alphabets. In [10] the same is shown for the LCP-matrices.

In conclusion matrix $\text{diag}(\mathbf{R} \cdot \Delta\mathbf{a}^{(21)})$ is nonsingular and $\mathbf{C}_{Div}$ has rank $r = N_{TX}$. This means matrix $\mathbf{B}$ has full rank $r = N_{TX}$, too [15]; the LSD space-time codes achieve the maximum diversity gain $N_{TX} \cdot N_{RX}$.

B. Coding for combined spatial multiplexing and diversity

We analyze the combination of spatial multiplexing and diversity: $1 < N_U \leq \text{rank}(\mathbf{H}) \leq \mathrm{N_{TX}}$. The block length of the outer code is $N_C = N_U \cdot N_L$, $N_C \geq N_{TX}$. To transmit the vector $\mathbf{b} = \mathbf{Ra}$ the $N_{TX} \times N_L$ code matrix $\mathbf{S}$ is given by:

$$\begin{aligned} [\mathbf{s}_{\nu=1}, \mathbf{s}_2, ..., \mathbf{s}_{\nu=N_L}] &= [\mathbf{C}_{\nu=1}, \mathbf{C}_2, ..., \mathbf{C}_{N_L}] \cdot \mathbf{D} \\ \mathbf{S} &= \mathbf{C}_{SM} \cdot \mathbf{D} \qquad (10) \end{aligned}$$

with the $N_{TX} \times N_C$ matrix $\mathbf{C}_{SM}$ and the $N_C \times N_L$ matrix

$$\mathbf{D} = \begin{pmatrix} \mathbf{b}_{\nu=1} & \mathbf{0}_{N_U \times 1} & \mathbf{0}_{N_U \times 1} & \dots & \mathbf{0}_{N_U \times 1} \\ \mathbf{0}_{N_U \times 1} & \mathbf{b}_{\nu=2} & \mathbf{0}_{N_U \times 1} & \dots & \mathbf{0}_{N_U \times 1} \\ \vdots & & \vdots & \ddots & \vdots \\ \mathbf{0}_{N_U \times 1} & \mathbf{0}_{N_U \times 1} & \mathbf{0}_{N_U \times 1} & \dots & \mathbf{b}_{\nu=N_L} \end{pmatrix} \qquad (11)$$

$\mathbf{0}_{N_U \times 1}$ defines a $N_U \times 1$ vector containing zeros.

The diversity gain in this case is determined by the rank of the $N_{TX} \times N_L$ matrix $\mathbf{B} = \mathbf{S}^{(1)} - \mathbf{S}^{(2)} = \mathbf{C}_{SM} \cdot (\mathbf{D}^{(1)} - \mathbf{D}^{(2)})$. Matrix $(\mathbf{D}^{(1)} - \mathbf{D}^{(2)})$ has rank N_L because it consists of N_L linear independent column and row vectors. Matrix $\mathbf{C}_{SM}$ has rank N_{TX} because of the construction (details of the structure of $\mathbf{C}_\nu$ can be found in section II).

For $N_C = N_{TX}$ the $N_{TX} \times N_C$ matrix $\mathbf{C}_{SM}$ becomes square; therefore $\mathbf{B}$ as the product of $\mathbf{C}_{SM}$ and $(\mathbf{D}^{(1)} - \mathbf{D}^{(2)})$ has full rank $r = N_L$ [15]: This means, the LSD codes achieve *maximum diversity even in a combination with spatial multiplexing*.

Increasing the number N_U of spatial subchannels (i.e. increasing the spatial multiplexing gain) leads to a decreasing diversity gain because $r = N_L = \frac{N_C}{N_U}$ (*diversity - multiplexing tradeoff*). In the case of $N_U = N_{TX} = N_C$ (pure spatial multiplexing) no transmit diversity gain is achieved ($N_L = 1$).

C. Adaptation of diversity and coding gain

As shown in the previous section the LSD Codes achieve full diversity; adaptations of block length N_C and code rate $r_C = \frac{N_I}{N_C}$ of the outer code lead to different results regarding diversity and coding gain.

E.g., for a 2×2 MIMO system using $N_U = 2$ spatial subchannels the maximum rank r of the Tx symbol matrix $\mathbf{S}$ is 1 for $N_C = 2$; for $N_C = 4$ the LSD codes achieve rank 2, that doubles the diversity gain. For a system with $N_{TX} = 2$ Tx antennas using $N_U = 1$ spatial subchannel LSD codes achieve a Tx diversity gain of $r = 2$ for $N_C = 2$ and also for $N_C = 3$; but $N_C = 3$ leads to a higher coding gain, as the cumulative density function (CDF) plots in Fig. 3 show (the right shift for $N_C = 3$). The LSD code design uses optimized inner codes for the case of $N_C > N_{TX}$ (in the case of pure Tx diversity this leads to a better performance than Tx antenna switching, see [2] for details).

In Fig. 3 and in the following CDF plots all possible matrices $\mathbf{A} = \mathbf{BB}^H$ are analyzed; 4QAM is used, according to (7) G is calculated for all pairs of the 4^{N_I} different Tx symbol matrices $\mathbf{S}$. The Tx symbol matrix $\mathbf{S}$ is normalized to $E[\text{trace}(\mathbf{SS}^H)] = N_C$;

For the LSD codes a simple reduction of the code rate r_C can be done by deleting columns of the outer code matrix R and adapting the length of the Tx symbol vector $\mathbf{a}$; reducing the code rate leads to higher coding gains, as shown in Fig. 4. Because of the linearity of the LSD codes a large number of suboptimal low-complexity equalizers can be used for decoding. E.g. a MMSE filter shows a very low complexity but a weak performance compared to a ML decoder. But reducing the outer code rate r_C improves the performance of suboptimal decoders [16].

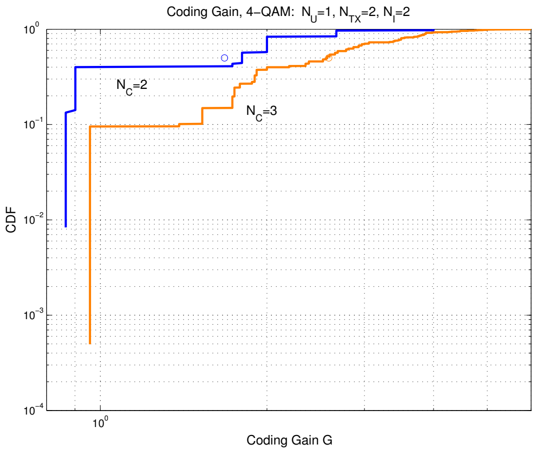

Fig. 3. CDF of coding gain: Comparison of different block lengths N_C for LSD codes

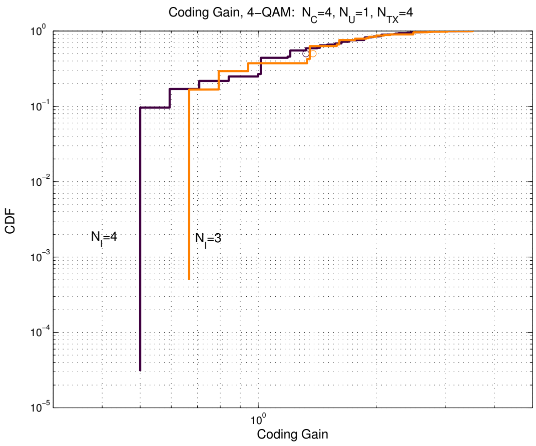

Fig. 4. CDF of coding gain: Comparison of different code rates $r_C = \frac{N_I}{N_C}$ for LSD codes

IV. Comparison to Other Space-Time Codes

a) ST-LCP codes: These space-time codes use a LCP matrix as outer code combined with a Tx antenna array to exploit Tx diversity. In the following Tx antenna switching is used as one proposed method to drive the antenna array [10]. I.e., these codes can be described as LSD codes with LCP matrix as outer code in pure diversity mode ($N_U = 1$) where the inner code vectors $\mathbf{c}_\nu$ are columns of $\mathbf{I}_{N_{TX}}$ (Tx antenna switching) and $N_C = N_{TX}$.

In [10] LCP matrices are presented; one sort, called LCP-A, are suitable for block lengths $N_C = 2^n$ with $n \in \mathbb{N}$. For other block lengths the LCP-B matrices are given; LCP-B matrices show a lower performance compared to LCP-A matrices. Fig. 5 shows that the performance for the LCP-A matrices is better than the performance of the LSD coding scheme using the optimized chirp matrix $\mathbf{R}$ as outer code, for $N_U = 1$ (pure Tx diversity) as well as for $N_U = 2$. But the chirp matrices perform better than the LCP-B matrices; an example is shown in Fig. 6 for $N_C = 6$. The CDF plots in Fig. 7 and Fig. 8 confirm these results: For block lengths that are a power of two the LCP-A matrix is the better choice, but for other block lengths the optimized chirp matrix of the LSD codes

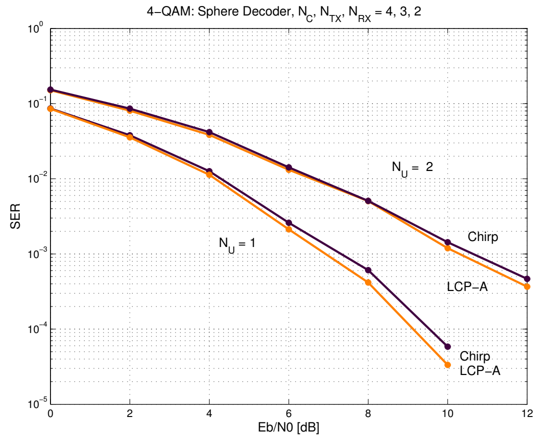

Fig. 5. SER performance: Comparison of ST-LCP and LSD codes

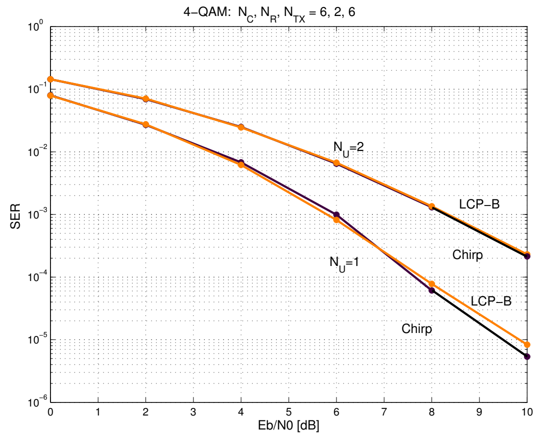

Fig. 6. SER performance: Comparison of ST-LCP and LSD codes

outperforms the LCP-B matrix.

b) Khatri-Rao Codes: These codes use a LCP matrix as outer code and a Vandermonde matrix as inner code [11]. They allow a flexible adaptation from pure Tx diversity ($N_U = 1$) - over a combination of Tx diversity ($1 < N_U < N_{TX}$) and spatial multiplexing - up to pure spatial multiplexing ($N_U = N_{TX}$). In the pure diversity mode there is no difference between the coding gain of the ST-LCP codes and the Khatri-Rao codes. Both use the same outer coding matrices and their inner coding matrices behave similarly. The results of the analysis of the coding gain G in Fig. 7 and Fig. 8 show a higher coding gain for Khatri-Rao codes that use a LCP-A matrix but a lower gain for a LCP-B matrix when compared to LSD codes with same block length and number of spatial subchannels.

c) Linear Dispersion Codes: These codes also allow a combination of Tx diversity and spatial multiplexing, but because of their design described in [9] - they are found by a numerical solution of an optimization problem with the mutual information as the objective function - they do not guarantee the maximum Tx diversity. We analyzed two different LD codes, the code given by equation (36) in [9] and the code according to (39) in [9]. We observed in our analysis of diversity and coding gain for 4QAM that about 3.2 % of

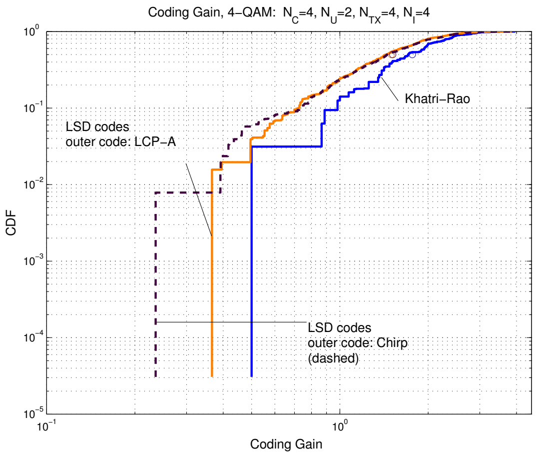

Fig. 7. CDF of coding gain: Comparison of Khatri-Rao and LSD codes

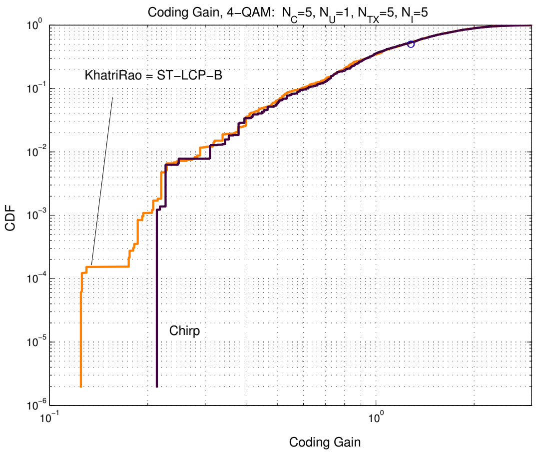

Fig. 8. CDF of coding gain: Comparison of Khatri-Rao and LSD codes

all possible difference matrices $\mathbf{B}$ (see section III) have not full rank for (36), about 1% for (39). For the cases with full diversity the CDF of the coding gain for (36) is shown in Fig. 9; the coding gain is higher than in the case of comparable LSD codes (even when a LCP-A matrix is used as outer code $\mathbf{R}$). For the second LD code (39) different results are found. The coding gain of the comparable LSD code ($N_{TX} = 3$, $N_C = 6$, $N_U = 1$, $N_L = 6$) is higher, the results are listed in Table I.

	min(G)	max(G)	mean(G)
LD	0.5291	7.7354	3.1556
LSD	0.6370	8.0000	3.6913

TABLE I

CODING GAIN G: LD (39) AND LSD CODES

V. CONCLUSIONS

LSD codes are able to achieve full spatial and temporal diversity and allow to trade spatial multiplexing gain (data rate) for diversity gain (link reliability) in a flexible way. The coding gain of these codes can be adapted to different demands (e.g. low-complexity decoder, especially in combination with rich arrays). The block length N_C is decoupled from the Tx antenna array; this opens up a large performance - complexity tradeoff. The optimized chirp matrix as outer code shows higher coding gains than the LCP-B matrix.

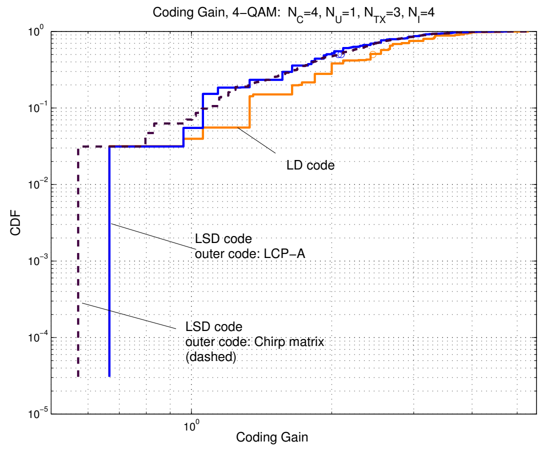

Fig. 9. CDF of coding gain: Comparison of LD and LSD codes

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