Space-Time Processing for Cooperative Relay Networks

Ingmar Hammerstroem, Marc Kuhn, Boris Rankov and Armin Wittneben
Swiss Federal Institute of Technology (ETH) Zurich
Communication Technology Laboratory, CH-8092 Zurich, Switzerland
Email: {hammerstroem, kuhn, rankov, wittneben}@nari.ee.ethz.ch

***Abstract*— Future wireless communication systems have to support high data rates. The capacity of these systems can be increased dramatically by using multiple antennas at the transmitter and the receiver working in a rich scattering environment. But in a line-of-sight environment the MIMO channel matrix is rank deficient and therefore the capacity increase diminishes. Using cooperative *amplify & forward* relay nodes it is possible to overcome this problem by increasing the rank of the MIMO channel. A special signaling scheme is necessary to achieve this increase of channel rank. Therefore the use of existing space-time algorithms is not straightforward. In this paper we show that a recently proposed class of linear space-time block codes exploits the offered capacity and achieves good performance results. The codes are able to use jointly transmit diversity in combination with spatial multiplexing with reasonable and scalable computational complexity.**

I. Introduction

Future wireless broadband communication systems will operate beyond 5 GHz, for example Wireless Local Area Networks (WLAN) in the ISM Band at 24 GHz. For such systems link level throughput requirements may demand a spectral efficiency beyond 10 bits/channel use. Probably MIMO (Multiple Input Multiple Output) wireless is the only feasible approach to achieve this spectral efficiency.

Antenna arrays at the transmit and/or receive side introduce additional degrees of freedom (spatial dimension) into a wireless communication system. There are two basic space-time processing methods which make use of these degrees of freedom in MIMO systems, 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 [1]. With spatial multiplexing it is possible to enhance the data rate without additional cost of bandwidth or power by transmitting parallel substreams simultaneously over spatial subchannels which are available in a rich scattering environment [2].

With increasing frequency it is possible to accommodate a large number of antennas in a given volume (“rich array”) because the array size scales down and the decorrelation distance decreases. The array gain of a large number of antennas can compensate for the path loss which is proportional to the square of the frequency; and the more antennas are used the more MIMO techniques become efficient - provided a rich scattering environment. However, for frequencies beyond 5 GHz there is a major obstacle in the practical exploitation of MIMO technology: the rich scattering requirement. The additional degrees of freedom depend on the multipath propagation environment and the efficiency of the space-time processing methods diminishes with increasing correlation of the channel coefficients. In the high frequency regime there is an increase in correlation because the propagation channel becomes more and more line-of-sight (LoS). Fig. 1 shows the degradation of the MIMO channel capacity with increasing Ricean $K-$factor. Especially in a pure LoS environment without any multipath propagation the MIMO channel has rank one which makes the use of spatial multiplexing impossible. In the following we consider only transmissions over such pure LoS channels with free-space loss and without any small-scale fading effects; that means worst case assumptions for the application of MIMO techniques.

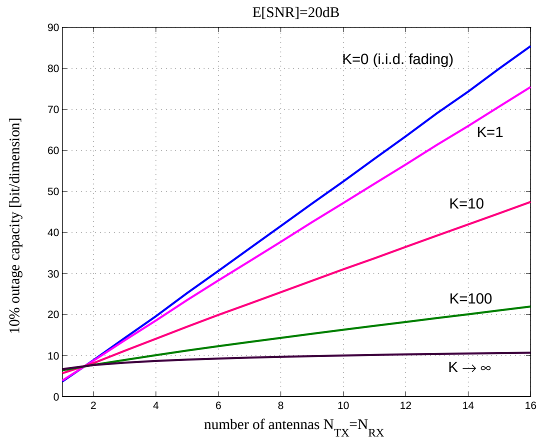

Fig. 1. 10% outage capacity of Rayleigh and Ricean fading MIMO channels

In [3] it is shown that by node cooperation at the Physical Layer (PHY), e.g. cooperative relaying, it is possible to increase the rank of MIMO channels. The main idea of cooperative relaying is to have multiple idle nodes (or special relays) assisting the communication of active nodes. In this work we consider a 2-hop relay network using linear *amplify and forward* relay nodes; this way of relaying allows a lower power consumption at the relaying nodes because there is no need of signal processing power for decoding (idle nodes in a low power mode are an example for amplify and forward relays). Improving the rank of the channel matrix leads to a higher information rate of the communication channel; therefore the application of MIMO techniques, in particular spatial multiplexing, is possible. Beyond the rank improvement there are further advantages of cooperative relaying: it is well known that multihop communication increases the coverage and reduces the total transmit power of a network.

To date cooperative relaying schemes have primarily been proposed to achieve diversity [4], [5] .

The contributions of this paper are a cooperative signalling scheme using amplify and forward relays to enable MIMO techniques and a high rate space-time coding scheme that can be adapted to the properties of these channels and exploits their capacity using spatial multiplexing and allowing to trade spatial multiplexing gain for diversity gain.

II. Relaying Scheme

Fig. 2 illustrates the proposed cooperative MIMO system. The source has N_{TX} and the destination N_{RX} antennas. In

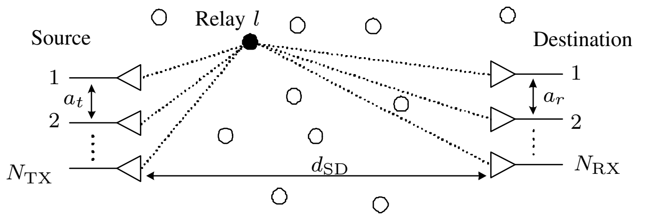

Fig. 2. A 2-hop relay network with antenna arrays at source and destination

contrast the relays do not necessarily feature multiple antennas. In this example the transmission of a data packet from the source to the destination occupies two time slots. The first time slot is allocated to the source exclusively. The relays receive during the first time slot and retransmit an amplified version of the received analog signal during the second time slot. The goal of the node cooperation is to increase the rank of the compound (two time slots) channel matrix and to shape the eigenvalue distribution such that the achievable rate of the MIMO link improves.

Note, that the relay nodes in Fig. 2 can be viewed as "active" omni-directional scatterers which establish a sort of multipath channel. A major difference to passive scattering is that the relay nodes add noise to the forwarded signal.

A. System Model

A source with N_{TX} transmit antennas sends information to a destination with N_{RX} receive antennas. N_{R} relay nodes assist the communication in order to increase the channel rank and the achievable information rate. In this paper we consider only single-antenna relay nodes. The extension to the multi-antenna case is straightforward.

In time slot k the source sends the baseband equivalent discrete-time $(N_{\mathrm{TX}} \times 1)$ vector $\mathbf{s}_k$. The signals received by the relays and the destination in time slot k are given by

$$\mathbf{y}_k = \mathbf{H}_1 \mathbf{s}_k + \mathbf{w}_{k,\mathrm{R}} \quad (1)$$

$$\mathbf{r}_k = \mathbf{H}_0 \mathbf{s}_k + \mathbf{w}_k . \quad (2)$$

where the $(N_{\mathrm{R}} \times 1)$ vector $\mathbf{y}_k$ contains the receive signals at the relays, the $(N_{\mathrm{RX}} \times 1)$ vector $\mathbf{r}_k$ the receive signals at the destination, $\mathbf{w}_{k,\mathrm{R}}$ and $\mathbf{w}_k$ the AWGN contributions at the relays and the destination receiver, respectively. $\mathbf{H}_0 \in \mathbb{C}^{N_{\mathrm{RX}} \times N_{\mathrm{TX}}}$ contains the channel coefficients of the direct link between source and destination and $\mathbf{H}_1 \in \mathbb{C}^{N_{\mathrm{R}} \times N_{\mathrm{TX}}}$ the channel coefficients between source and relays (first hop).

In the next time slot $k+1$, the relays send $\mathbf{G}\mathbf{y}_k$ to the destination and the source is quiet. The diagonal $(N_{\mathrm{R}} \times N_{\mathrm{R}})$ matrix $\mathbf{G}$ contains the analog gain factors of the relays. Note that the relays are not able to receive in time slot $k+1$, since they are already forwarding the signals from the previous time slot and practical considerations (antenna coupling) prevent the relay nodes from transmitting and receiving concurrently at the same physical channel.

Thus, in time slot $k+1$ the destination receives

$$\widetilde{\mathbf{r}}_{k+1} = \mathbf{H}_2 \mathbf{G} \mathbf{y}_k + \mathbf{w}_{k+1}. \quad (3)$$

The matrix $\mathbf{H}_2 \in \mathbb{C}^{N_{\mathrm{RX}} \times N_{\mathrm{R}}}$ contains the channel coefficients between the relays and the destination (second hop). By inserting (1) into (3) and separating signal and noise terms we obtain

$$\widetilde{\mathbf{r}}_{k+1} = \mathbf{H}_2 \mathbf{G} \mathbf{H}_1 \mathbf{s}_k + \mathbf{H}_2 \mathbf{G} \mathbf{w}_{k,\mathrm{R}} + \mathbf{w}_{k+1}. \quad (4)$$

Due to the gain matrix $\mathbf{G}$ and the channel matrix $\mathbf{H}_2$ the resulting noise at the destination in time slot $k+1$ is in general colored. Let $\mathbf{n}_{k+1} = \mathbf{H}_2 \mathbf{G} \mathbf{w}_{k,\mathrm{R}} + \mathbf{w}_{k+1}$ denote this noise component. Defining the two-hop relay channel as

$$\widetilde{\mathbf{H}}_{12} = \mathbf{H}_2 \mathbf{G} \mathbf{H}_1 \quad (5)$$

and describing both time slots jointly in a stacked vector

$$\widetilde{\mathbf{r}}_{k,k+1} = \begin{bmatrix} \mathbf{r}_k \\ \widetilde{\mathbf{r}}_{k+1} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H}_0 \\ \widetilde{\mathbf{H}}_{12} \end{bmatrix}}_{\widetilde{\mathbf{H}}} \mathbf{s}_k + \begin{bmatrix} \mathbf{w}_k \\ \mathbf{n}_{k+1} \end{bmatrix} \quad (6)$$

leads to an channel matrix $\widetilde{\mathbf{H}}$ describing a $(N_{\mathrm{TX}} \times 2N_{\mathrm{RX}})$ MIMO channel with spatially colored additive Gaussian noise.

B. Information Rate

It is shown in [3] that an equivalent receive signal can be written as

$$\mathbf{r}_{k,k+1} = \begin{bmatrix} \mathbf{r}_k \\ \mathbf{r}_{k+1} \end{bmatrix} = \underbrace{\begin{bmatrix} \mathbf{H}_0 \\ \mathbf{H}_{12} \end{bmatrix}}_{\mathbf{H}} \mathbf{s}_k + \begin{bmatrix} \mathbf{w}_k \\ \mathbf{\Lambda}^{-1/2} \mathbf{n}_{k+1} \end{bmatrix}, \quad (7)$$

with $\mathbf{H}_{12} = \mathbf{\Lambda}^{-1/2} \widetilde{\mathbf{H}}_{12}$. $\mathbf{\Lambda}$ denotes a scaled version of the autocovariance matrix of $\mathbf{n}_{k+1}$ and is given by

$$\mathrm{E}\left[\mathbf{n}_{k+1} \mathbf{n}_{k+1}^H\right] = \sigma^2 \left(\mathbf{H}_2 \mathbf{G} \mathbf{G}^H \mathbf{H}_2^H \frac{\sigma_{\mathrm{R}}^2}{\sigma^2} + \mathbf{I}_M \right) = \sigma^2 \mathbf{\Lambda},$$

where $(\cdot)^H$ denotes conjugate transpose, σ^2 and σ_{R}^2 the noise variance at the destination and the relays, respectively.

The information rate $I(\mathbf{s}_k; \mathbf{r}_{k,k+1} | \mathbf{H}) = I(\mathbf{s}_k; \widetilde{\mathbf{r}}_{k,k+1} | \widetilde{\mathbf{H}}) = I_{\mathbf{H}}$ (mutual information) in bits per channel use follows then readily [6] by

$$I_{\mathbf{H}} = \frac{1}{2} \log_2 \det \left(\mathbf{I}_{N_{\mathrm{RX}}} + \frac{P}{N_{\mathrm{TX}} \cdot \sigma^2} \mathbf{H} \mathbf{H}^H \right) \quad (8)$$

where $P = \mathrm{E}\left[\mathbf{s}_k^H \mathbf{s}_k\right]$ is the average transmitted power at the source, whereby no CSI at the transmitter is assumed.

The average mutual information I is given by the expectation $\mathrm{E}_{\mathbf{H}}[I_{\mathbf{H}}]$. The randomness of $\mathbf{H}$ is due to the random location of the relays and/or the channel model. Note that (8) is a lower bound on the capacity of the general relay channel with a finite number of relays, which is not known yet.

III. Space-Time Coding and Decoding Scheme

A. Coding scheme

In the following we give a description of the in [7] and [8] proposed linear space-time codes, which are used in this work. We refer to them as linear scalable dispersion (LSD) codes.

The code consists of two concatenated but 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.

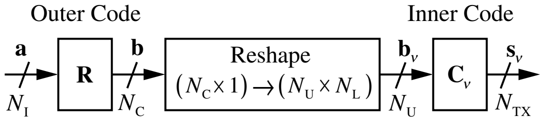

Fig. 3. Symbol discrete model of the space-time encoding scheme

A time series representation of the coding scheme is depicted in Fig. 3. The input symbol vector $\mathbf{a}$, consisting of N_I information symbols, is multiplied with the $(N_\mathrm{C}\times N_\mathrm{I})$ outer code matrix $\mathbf{R}$ to form the transmit symbol vector $\mathbf{b}$. The dimensions of the code matrix determine the code rate to $\frac{N_\mathrm{I}}{N_\mathrm{C}}$. Thereafter the transmit symbol vector $\mathbf{b}$ of dimension $(N_\mathrm{C}\times 1)$ is reshaped into a $(N_\mathrm{U}\times N_\mathrm{L})$ matrix. The columns of this matrix are the consecutive $N_\mathrm{L}=\frac{N_\mathrm{C}}{N_\mathrm{U}}$ input vectors $\mathbf{b}_\nu$ of the linear time-variant inner code $\mathbf{C}_\nu$, whereas ν is the time index. Note that the vectors $\mathbf{s}_\nu$ are only transmitted in odd timeslots k at the N_TX transmit antennas.

The system transmits $N_\mathrm{U}\leq\mathrm{rank}\,(\mathbf{H})$ symbols in one timestep, where $\mathbf{H}$ is the MIMO channel matrix. We refer to N_U as the number of *spatial subchannels* to be used for spatial multiplexing. 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 $(N_\mathrm{TX}, N_\mathrm{U})$ and the channel statistics (Rayleigh or Ricean fading). Pure TX diversity $(N_\mathrm{U}=1)$, spatial multiplexing $(N_\mathrm{U}=\mathrm{rank}\,(\mathbf{H}))$ or a combination of both $(N_\mathrm{U}\leq\mathrm{rank}\,(\mathbf{H}))$ are possible configurations of the inner code. In [7] efficient code matrices are presented for TX diversity and joint TX diversity and spatial multiplexing.

The outer code $\mathbf{R}$ is optimized for diversity performance and achieves a high diversity gain and an excellent performance in a fading environment even at code rate $r_C=1$, which is considered throughout this work. Due to this form of code concatenation a flexible trade-off between spatial multiplexing gain and diversity gain is possible.

B. Decoding scheme

The destination performs temporal maximum ratio combining along the time-axis, by adding up the results of the multiplication of the received vectors $\mathbf{r}_k$ and $\mathbf{r}_{k+1}$ of both

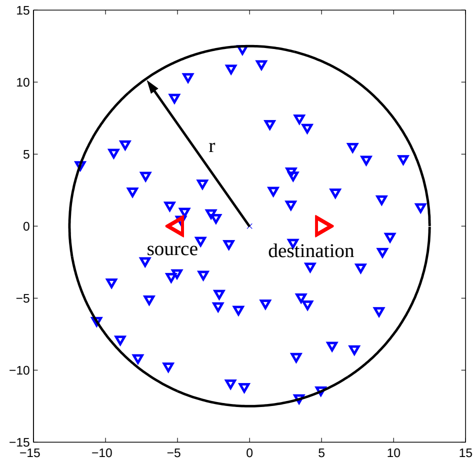

Fig. 4. Relay assisted MIMO communication link; source and destination fixed; relays randomly uniform distributed over the disk

timeslots with the channel matched matrices $\mathbf{H}_0^H$ and $\mathbf{H}_{12}^H$, respectively. The output is then given by

$$\hat{\mathbf{s}}_\nu=\mathbf{H}^H\mathbf{r}_{k,k+1}, \tag{9}$$

where the $\mathbf{H}$ and $\mathbf{r}_{k,k+1}$ are defined in (7). After the multiplication of $\hat{\mathbf{s}}_\nu$ with the inner code matched matrix $\mathbf{C}_\nu^H$ reshaping is done the other way around: N_L column vectors $\hat{\mathbf{b}}_\nu$ of length N_U form a column vector $\hat{\mathbf{b}}$ of length N_C. Multiplication with the outer code matched matrix $\mathbf{R}^H$ leads to the vector $\mathbf{d}$, that is processed by a decoder to get the estimation of the input symbol vector $\hat{\mathbf{a}}$.

The task of the decoder is the compensation of intersymbol interference (ISI) which results from interfering spatial subchannels and from the optimized diversity performance of the outer code in fading. In [9] a suboptimal ISI decoder (MAP-DFE) is presented. The decoder uses a scalable interference cancellation method by applying a posteriori information and achieves very high performance. For the considered codes this decoder shows a better performance and a lower complexity than the BLAST decoder (MMSE-DFE).

IV. Performance Results

Simulation Setup: Fig. 4 depicts an example of a 2-hop relay network. The source node is located at coordinates $(-d_\mathrm{SD}/2,0)$ and the destination node at $(0,d_\mathrm{SD}/2)$. The relay nodes are randomly placed in the disk of area πr^2 according to a uniform distribution. In our simulations we choose the distance between source and destination $d_\mathrm{SD}=800$ and $r=1000$ wavelengths, respectively. The source and the destination node are equipped with multiple antennas, whereby the relay nodes have only one antenna. We assume as a worst case scenario (in terms of correlation of channel coefficients) for the whole simulation set a path loss channel model (no multipath) with a power path loss exponent $\alpha=2$:

$$h_{ij}=\frac{1}{d_{ij}^{\alpha/2}}\cdot e^{-j2\pi d_{ij}/\lambda}, \tag{10}$$

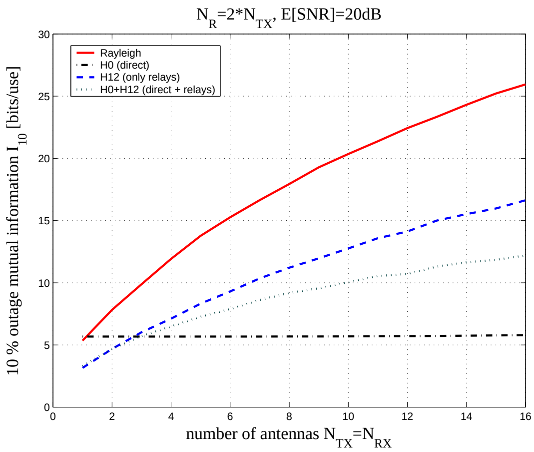

Fig. 5. 10% outage rate (mutual information) vs. the number of antennas; comparison of relay assisted MIMO channel matrix with i.i.d. channel matrix and LoS channel matrix

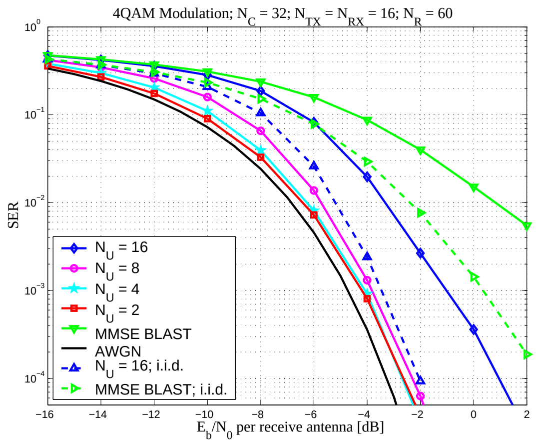

Fig. 6. Symbol Error Rate over E_{b}/N_0 per receive antenna; only $\mathbf{H}_{12}$ with $N_{\mathrm{R}} = 60$ is used; Various number of used subchannels; compared with uncoded (MMSE-BLAST) and AWGN case (16 RX antennas); comparison with i.i.d. channel matrices for LSD $N_{\mathrm{U}} = 16$ and MMSE-BLAST (dashed lines)

where h_{ij} denotes the channel coefficient between transmit antenna j and relay i (receive antenna i and relay j, respectively), d_{ij} is the corresponding distance and λ the operational wave length.

The gain coefficients in the amplify-and-forward relays are chosen according to

$$[\mathbf{G}]_{ll} = \sqrt{\frac{Q_l}{\|\mathbf{H}_{1,l}\|^2 P/N_{\mathrm{TX}} + \sigma_{\mathrm{R}}^2}} \tag{11}$$

where $Q_l = P/N_{\mathrm{R}}$ denotes the maximum transmit power of relay l and $\|\mathbf{H}_{1,l}\|$ the norm of the l-th row of matrix $\mathbf{H}_1$, which contains the channel coefficients between the source and relay l. This gain allocation scheme is very power efficient, because the total transmitted power of all relays is equal to the power P transmitted by the source in the first timeslot and does not increase with the number of relays. Note, that this is in general a suboptimal power allocation and other strategies can achieve a better performance [3]. In this work it is assumed that the variance of the noise at the relays is equal to the variance at the destination $\sigma_{\mathrm{R}}^2 = \sigma^2$.

Outgoing from the system model in section II-A two different scenarios can be derived. In the first scenario the direct link between source and destination is obstructed, caused e.g. by shadowing effects (scenario: direct link blocked). Therefore the destination receives only from the relays in the even timeslots. In the second scenario there is a direct link component available at the destination and thus $\mathbf{H}_0$ is unequal to zero (scenario: direct link available).

In Fig. 5 we compare the 10% outage information rate of the relay assisted MIMO link with respect to a Rayleigh fading MIMO channel (upper bound) and a line-of-sight (LOS) MIMO channel (lower bound) on the basis of an equal average receive signal-to-noise ratio (SNR) of 20dB. All channel matrices are normalized such, that the average received signal power is equal to the transmitted power (no array gain) in order to highlight the performance gain due to the increased channel rank. In the Rayleigh and LOS case the source may transmit in every time slot, but with half the power $P/2$.

It can be seen that in the case of the first scenario (only $\mathbf{H}_{12}$), the performance is better than in the case of the second scenario ($\mathbf{H}_0$ and $\mathbf{H}_{12}$). This is due to the fact, that the channel coefficients become more correlated with a direct link component and because of the normalization of the receive power to the transmit power. In reality an additional link component would increase the received SNR.

In the following we analyze the performance of the considered space-time coding scheme based on computer simulations. While not stated explicitly we use the decoder presented in [9].

A. Scenario: direct link blocked

Applying the described coding scheme it is possible to trade data rate and link reliability in a very flexible way. Fig. 6 illustrates this trade-off by depicting the impact of the number of used subchannels N_{U} on the error performance. A system with $N_{\mathrm{TX}} = N_{\mathrm{RX}} = 16$ antennas at the source and the destination and $N_{\mathrm{R}} = 60$ number of relays is considered. The performance results of this antenna and relay configuration assuming a BLAST system (no outer code, pure spatial multiplexing, MMSE-BLAST as decoder) and an AWGN channel are plotted as references here. For $N_{\mathrm{U}} = 16$ spatial subchannels we achieve full rate (pure spatial multiplexing). By decreasing the number of spatial subchannels N_{U} and therefore the data rate we achieve a decrease in SER, too.

As a second reference the performance of the considered coding scheme with $N_{\mathrm{U}} = 16$ and the BLAST system is plotted using channel matrices with i.i.d. fading coefficients instead of $\mathbf{H}_{12}$. The loss of performance is due to the correlation of the coefficients in the channel matrix $\mathbf{H}_{12}$.

The influence of the correlation on the product of eigenvalues for the assumed gain allocation scheme is shown in Fig. 7. The cumulative distribution functions (CDF) of the product of eigenvalues of $\mathbf{H}_{12}$ with different numbers of relays are depicted in comparison to channel matrices with i.i.d. fading coefficients. It can be seen that the product of eigenvalues of

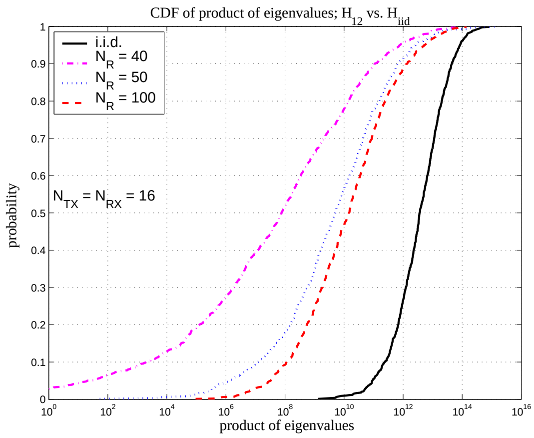

Fig. 7. CDF of product of eigenvalues $\mathbf{H}_{12}$ with various number of relays vs. a MIMO channel matrix with i.i.d. coefficients $\mathbf{H}_{\mathrm{iid}}$; $N_{TX} = N_{RX} = 16$

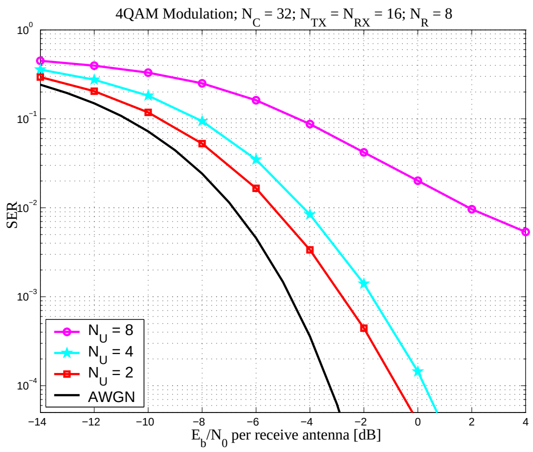

Fig. 8. Symbol Error Rate over E_{b}/N_0 per receive antenna; only $\mathbf{H}_{12}$ with $N_{\mathrm{R}} = 8$ is used; Various number of subchannels; compared with AWGN

$\mathbf{H}_{12}$ is smaller and shows a greater variance. By increasing the number of relays the product of eigenvalues increases and the variance gets smaller.

In some cases the number of relays of $N_{\mathrm{R}} = 60$ seems to be unrealistic for a practical system. In Fig. 8 the error performance of the same system as above but with $N_{\mathrm{R}} = 8$ is shown. Due to this choice of N_{R} the maximal rank of $\mathbf{H}_{12}$ is bounded to 8. In this case full spatial multiplexing (e.g. BLAST) is impossible. Due to the flexible choice of N_{U} our proposed coding scheme is still able to use up to 4 spatial subchannels and to achieve good error performance.

B. Scenario: direct link available

In this LoS scenario the destination receives the transmitted signal over a rank one channel in the first timeslot. Therefore the destination is not able to decode the signal for $N_{\mathrm{U}} > 1$ until receiving the signals from the relays. Nevertheless, the destination does not need the received signal of the first timeslot for decoding. Is there any need for the received signal of the first timeslot? Fig. 9 shows the error performance for various number of subchannels N_{U} over $\frac{E_{\mathrm{b}}}{N_0}$ received in the second timeslot (as in Fig. 6). Considering the direct

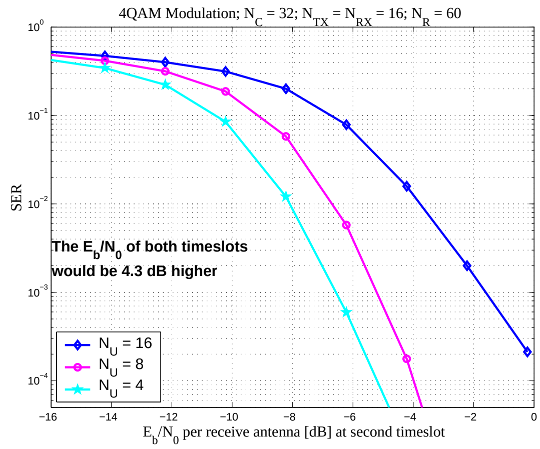

Fig. 9. Symbol Error Rate over E_{b}/N_0 per receive antenna at the second timeslot; both timeslots considered; $N_R = 60$; E_b/N_0 of both timeslots is 4.3 dB higher; Various number of used subchannels

link component the joint received power of both timeslots is increased. For our setup, we received in average 62.5% of the whole received signal power in the first timeslot and only 37.5% in the second. Therefore the direct link increased the $\frac{E_{\mathrm{b}}}{N_0}$ by 4.3 dB. It can be seen that in comparison to the curves in Fig. 6 we achieve a gain in error performance, especially for a smaller number of spatial subchannels.

V. Conclusions

We presented a cooperative signalling scheme using amplify and forward relays to enable MIMO techniques and a high rate space-time coding scheme that can be adapted to the properties of these channels and exploits their capacity using spatial multiplexing and allowing to trade spatial multiplexing gain for diversity gain. This flexibility is an important property, because of the strong dependency of channel conditions (e.g. rank) and the number of relays and their locations on the disk.

References

[1] V. Tarokh, N. Seshadri, and A. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Trans. Inform. Theory*, vol. 44, pp. 744–765, Mar. 1998.

[2] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell System Techn. J.*, vol. 1, pp. 41–59, Autumn 1996.

[3] A. Wittneben and B. Rankov, "Impact of cooperative relays on the capacity of rank-deficient MIMO channels," in *Proc. 12th IST Summit on Mob. and Wirel. Comm.*, pp. 421–425, Jun. 15–18, 2003.

[4] J. N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," submitted to IEEE Trans. Inform. Theory, 2002.

[5] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity – Part I & Part II," submitted to IEEE Trans. Commun., 2003.

[6] I. E. Telatar, "Capacity of multi-antenna Gaussian channels," Tech. Rep., AT&T Bell Laboratories, 1995.

[7] A. Wittneben and M. Kuhn, "A new concatenated linear high rate space-time block code," in *Proc. 55th IEEE Veh. Tech. Conf.*, vol. 1, pp. 289–293, May 6–9, 2002.

[8] M. Kuhn, I. Hammerstroem, and A. Wittneben, "Linear scalable space-time codes: Tradeoff between spatial multiplexing and transmit diversity," in *Proc. SPAWC*, Jun. 15–18, 2003.

[9] M. Kuhn and A. Wittneben, "A new scalable decoder for linear block codes with intersymbol interference," in *Proc. 55th IEEE Veh. Tech. Conf.*, vol. 4, pp. 1795–1799, May 6–9, 2002.