Distributed Interleave-Division Multiplexing Space-Time Codes for Coded Relay Networks

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***Abstract*—In this paper the application of the recently proposed Interleave-Division Multiplexing Space-Time Codes (IDM-STC) in coded relay networks is investigated. IDM-STC are a very flexible scheme to exploit space diversity with the benefits of IDM such as robustness against asynchronism and efficient iterative detection. While IDM-STC have been investigated for MIMO systems, relay networks induce additional constraints like imperfect decoding at the relay and limited cooperation. Consequently, not only the choice of the diversity scheme, but also the applied relay functionality significantly influences the overall performance. In this paper different relay schemes in combination with IDM-STC are considered for coded relay networks. Amplify-Forward (AF) does not assume any signal processing at the relays and just forwards the received signal. Decode-Forward (DF) fully decodes the received signal which can lead to error propagation. Another relaying scheme called Estimate-Forward (EF), which combines the advantages of AF and DF, was recently extended to coded systems and is called Decode-Estimate-Forward (DEF). A coded IDM-STC relay system with different relay schemes is investigated to show the good performance of IDM-STC combined with DEF in realistic scenarios with small overhead and robustness against asynchronism.**

I. Introduction

Multiple-Input Multiple-Output (MIMO) systems have been intensively investigated in the last years. Depending on the considered system, either multiplexing techniques like V-BLAST or diversity techniques as Space-Time Codes (STC) are applied to deal with severe fading in wireless scenarios. More recently, distributed relay systems have attracted much attention. Several relays assisting a source to transmit data to a destination build up a virtual MIMO (VMIMO) system where the relays are combined to a virtual antenna array (VAA). Due to this similarity to classical MIMO systems, diversity techniques known to be powerful for MIMO, can be adopted to relay networks. Many approaches to apply STC in relay networks have been proposed in the last years, however, several restrictions in relay networks have not been addressed. One important point is the imperfect cooperation between the virtual antennas. It is not possible to achieve perfect cooperation in terms of knowledge of all channel states and decoded data of the other relays with reasonable signaling overhead. Even synchronization is a hard task in a system with distributed relays. Consequently, some approaches are hard to apply to VMIMO directly as, e.g., Orthogonal Space-Time Block Codes (OSTBC).

A Space-Time Code based on Interleave Division Multiplexing (IDM) was introduced in [1] and [2] which does not need synchronization or any knowledge about other antennas. This IDM-STC is a very promising diversity technique also for VMIMO systems with small signalling overhead and robustness against asynchronism.In [3] IDM-STC was applied to a multi-user cooperative system. The focus was on high throughput at the cost of nearly full cooperation between the users requiring a large overhead. Additionally, despite of a repetition coded system, perfect decoding was assumed at all relays, which is a hard task in fading channels even with strong codes. In [4] an IDM-STC for an uncoded single-user relay system was considered, but only for Decode-Forward (DF) protocol.

However, not only the choice of the diversity scheme, but also the applied relay functionality significantly influences the overall performance. In this paper different relay schemes in combination with IDM-STC are considered for coded relay networks. Amplify-Forward (AF) does not assume any signal processing at the relays and just forwards the received signal. DF fully decodes the received signal which can lead to error propagation. In this case the results presented in [3] will not be achievable. To combine the advantages of AF and DF, Estimate-Forward (EF) was proposed in [5] for uncoded systems. EF forwards reliability information and therefore avoids error propagation and exploits the discrete signal alphabet. The idea of EF is the transmission of MMSE estimates conditioned on the received signal. This basic idea was recently extended to coded systems [6] and also to higher order modulation schemes [7]. This so-called Decode-Estimate-Forward (DEF) shows very good performance and is a reasonable choice in relay networks.

Transmission of Log-Likelihood Ratios (LLRs) is an alternative soft relay protocol called Decode-Amplify-Forward (DAF) and was investigated in combination with IDM-STC for an uncoded multi-user system in [8]. But as the DAF approach was already shown to be suboptimum in [6], we will not consider it here. In this paper a coded IDM-STC relay system with different relay schemes is investigated and the good performance of IDM-STC combined with DEF in realistic scenarios with small overhead and robustness against asynchronism is shown.

II. System Description

A. System Model

A system with one source S, one destination D and several parallel relays R_ν, $1 \leq \nu \leq N$, as shown in Figure 1 is considered. In the first time slot the source encodes the information bit vector $\mathbf{d}$ of length N_u with a channel code $\mathcal{C}$. The resulting code bit vector $\mathbf{b}\in[\pm 1]^{N_b}$ of length N_b is mapped on a QPSK symbol vector $\mathbf{c}$ of length N_c with $c[k]\in\{\pm 1 \pm j\}$ and transmitted to the relays in a broadcast manner. The relays estimate the code bits according to the applied relay protocol. Now the question arises, how the relays

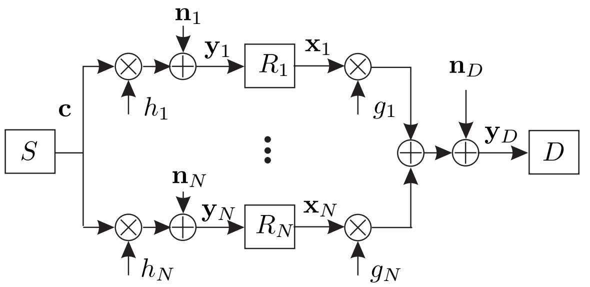

Fig. 1. Block diagram of a relay network with N parallel relays

should transmit their information to the destination. Applying a TDMA scheme would result in a large rate loss which increases with the number of relays. Hence, all relays should transmit at the same time to avoid this rate loss. But if all relays would transmit estimates of the same code bit simultaneously over a Rayleigh fading channel and their distances to the destination are nearly the same, the resulting channel would be a flat Rayleigh fading channel and there would be no diversity gain. A good strategy in terms of performance is given by beamforming, which leads to constructive addition of all signal parts at the receiver. However, it requires channel state information (CSI) at the transmitters also about all other relays' channels. Distributed space-time block codes show good performance without channel state information but require at least synchronous transmission of all relays. As these requirements are very hard to fulfill in a relay network, we consider IDM-STC to provide spatial diversity. Each relay interleaves the signal to be forwarded with a relay-specific interleaver to avoid a superposition of different copies of the same code bit. In other words, IDMA is applied at the relays to be able to distinguish the signals from different relays at the destination. These interleaved estimates are forwarded to the destination in the second time slot. At the destination these signals have to be separated with an iterative detection algorithm [9] similar to IDMA detectors. The knowledge that each relay transmitted the same information just with a different order is exploited within the iterative detection by combination of the signals from all relays. A detailed description of the detection is given in Section II-D. The complex channel coefficient between the source and relay R_ν is denoted by h_ν and between relay R_ν and the destination by g_ν; all channel coefficients are iid. The relays receive the source signal at time instant k weighted with the corresponding channel coefficient h_ν with $\mathrm{E}\{|h_\nu|^2\} = 1$ and the additive white Gaussian noise

$$y_\nu[k] = h_\nu \cdot c[k] + n_\nu[k],\; k = 1, \ldots, N_c\,. \tag{1}$$

The variance of the additive white Gaussian noise is assumed to be $\sigma_R^2/2$ per dimension for all relays to keep the derivations simple.

B. Relay Protocols

Several relay protocols defining the relay's functionality were proposed. The most common ones are DF and AF [10]. DF makes use of the discrete alphabet and of the coding gain in a coded system, but suffers from error propagation in the case of wrong decisions at the relay. AF ignores the benefits of channel coding and discrete alphabets, but avoids error propagation and preserves reliability information about the source-relay link. In the case of DF in an uncoded system with QPSK the estimation of the codebit becomes

$$\begin{aligned} \tilde{b}_\nu^{DF}[2k-1] &= \beta_\nu^{DF}\operatorname{sign}\{\mathcal{R}\{h_\nu^* y_\nu[k]\}\} \\ \tilde{b}_\nu^{DF}[2k] &= \beta_\nu^{DF}\operatorname{sign}\{\mathcal{I}\{h_\nu^* y_\nu[k]\}\}\,,\quad k = 1, \ldots, N_c \end{aligned} \tag{2}$$

where $\mathcal{R}$ and $\mathcal{I}$ denote the real and imaginary part, respectively and h_ν^* is the conjugate complex of h_ν. The parameter β denotes the normalization to the power constraint of the relay, which is set to 1 per dimension for the source and all relays for simplicity. This parameter depends on the relay function and ensures $\mathrm{E}\{|\tilde{b}_\nu|^2\} = 1$. In the case of DF β equals 1. In a coded system the hard decision is made after channel decoding at the relay. In the case of AF the phase rotation due to h_ν is corrected to be able to interleave estimates of the information bits and not only the symbols. This is only possible for BPSK and QPSK and results in

$$\begin{aligned} \tilde{b}_\nu^{AF}[2k-1] &= \beta_\nu^{AF}\cdot\mathcal{R}\left\{\frac{y_\nu[k]}{h_\nu}\right\} \\ \tilde{b}_\nu^{AF}[2k] &= \beta_\nu^{AF}\cdot\mathcal{I}\left\{\frac{y_\nu[k]}{h_\nu}\right\}\,. \end{aligned} \tag{3}$$

Additionally, the Decode-Estimate-Forward protocol will be considered forwarding soft information. For the uncoded case the optimal way of transmitting soft information in terms of the mean squared error (MSE) was derived analytically in [5] and is called Estimate-Forward. The conditional expectation $\mathrm{E}\{b|\mathbf{y}\}$ of the transmitted bits minimizes the MSE at the destination. In a coded system the knowledge of the code can be incorporated in the estimation as an additional constraint [6]

$$\tilde{b}_\nu^{EF}[k'] = \beta_\nu^{EF}\cdot\mathrm{E}\{b[k']|\mathbf{y}_\nu, \mathcal{C}\}\,,\; k' = 1, \ldots, N_b\,. \tag{4}$$

For binary signals this conditional expectation can be expressed in terms of LLRs as

$$\tilde{b}_\nu^{EF}[k'] = \beta_\nu^{EF}\tanh\left(L_\nu[k']/2\right) \tag{5}$$

and become the well-known *soft bit*. In the uncoded case with QPSK modulation these LLRs can be simply calculated by

$$\begin{aligned} L_\nu[2k-1] &= \mathcal{R}\left\{4\frac{h_\nu^* y_\nu[k]}{\sigma_R^2}\right\} \\ L_\nu[2k] &= \mathcal{I}\left\{4\frac{h_\nu^* y_\nu[k]}{\sigma_R^2}\right\} . \end{aligned} \quad (6)$$

The factor β_ν^{EF} is again chosen to fulfill the power constraint of the relays. In a coded system the a-posteriori-LLRs delivered by a soft-output decoder at the relay are used to determine the LLRs $L_\nu(b)$.

C. IDM Transmitter at the Relay

IDM-STC are applied to the network to be able to exploit the spatial diversity provided by a relay network without an inherent rate loss. The basic principle of the IDM transmitter at the relay can be seen in Figure 2. Regardless of the applied

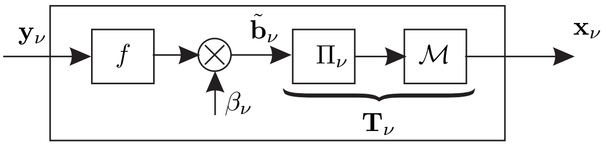

Fig. 2. Block diagram of relay R_ν

relay function denoted as f, the estimates $\tilde{b}_\nu$ are interleaved with a relay-specific interleaver Π_ν. After QPSK modulation the resulting signal $\mathbf{x}_\nu$ is transmitted to the destination. As the estimated code bits are distributed over time by the interleavers and over space by the relays, this scheme is a kind of Space-Time Code; each bit is transmitted over all relays at different time instances. To make the following derivations simpler, we include the interleaving and QPSK modulation in one matrix $\mathbf{T}_\nu$. Then $\mathbf{x}_\nu$ can be expressed in terms of $\tilde{\mathbf{b}}_\nu$ as

$$\mathbf{x}_\nu = \mathbf{T}_\nu \tilde{\mathbf{b}}_\nu . \quad (7)$$

As shown in [9], an iterative IDM detector is able to exploit the diversity at moderate cost of order $\mathcal{O}(N)$. Therefore, we will apply this interference canceler (IC) in the proposed IDM-STC system for detection at the destination. A detailed description of the overall detector is given in the next paragraph.

D. IDM-STC Receiver at the destination

The received signal at the destination is given by

$$\mathbf{y}_D = \sum_{\nu=1}^{N} g_\nu \cdot \mathbf{x}_\nu + \mathbf{n}_D = \sum_{\nu=1}^{N} g_\nu \cdot (\mathbf{T}_\nu \tilde{\mathbf{b}}_\nu) + \mathbf{n}_D \quad (8)$$

with $\mathbf{x}_\nu$ denoting the transmit signal of relay R_ν and $\mathbf{n}_D$ the noise at the destination. The low-complexity iterative IC at the destination is based on the Gaussian assumption. The parallel overall channels for each path including the S-R- and the R-D- hop and the relay depends on the relay protocol applied at the relays and may not be Gaussian anymore. Therefore we derive equivalent parameters for the different relay schemes to model a Gaussian channel with channel coefficient H_ν and noise variance σ_e^2. In the case of AF the effective channel coefficient H_ν of the ν-th path can be defined as

$$H_\nu^{AF} = g_\nu \cdot \beta_\nu^{AF} . \quad (9)$$

The performance of the iterative detection at the destination is limited by the additive noise as this disturbance remains even in the case of perfect interference cancellation. This overall effective noise variance becomes

$$\sigma_{e,AF}^2 = \sum_{\nu=1}^{N} \left(|H_\nu^{AF}|^2 \cdot \frac{\sigma_R^2}{|h_\nu|^2} \right) + \sigma_D^2 . \quad (10)$$

In contrast to this, H_ν and σ_e^2 in the case of DF become

$$H_\nu^{DF} = g_\nu \quad \text{and} \quad \sigma_{e,DF}^2 = \sigma_D^2 \quad (11)$$

as the destination assumes error-free detection at the relays.

In the case of DEF the overall disturbence is not Gaussian due to the nonlinear relay function. The exact distribution of the effective noise can be calculated and would improve the performance as shown in [11] but the difference is quite small so that we will use the Gaussian assumption proposed in [12] for simplicity. First we consider the channel up to the output of the relay. This Gaussian effective channel including h_ν and the relay has channel coefficient A_ν and noise η_ν representing the remaining error of the relay function. With this notation $\tilde{b}_\nu$ can be described by

$$\tilde{b}_\nu[k'] = A_\nu \cdot b[k'] + \eta_\nu[k'], \; k' = 1, \ldots, N_b \quad (12)$$

where $A_\nu = \left| \mathrm{E}\left\{ \tilde{b}_\nu | b = \pm 1 \right\} \right|$ is assumed to be known and the noise power being

$$\sigma_{\eta,\nu}^2 = \mathrm{E}\left\{b^2\right\} - A_\nu^2 = 1 - A_\nu^2 . \quad (13)$$

In both cases the expectation is done over one transmission block, so both parameters are constant for one block. This results in an overall channel from source to destination with

$$H_\nu^{EF} = A_\nu g_\nu \quad \text{and} \quad \sigma_{e,EF}^2 = \sum_{\nu=1}^{N} |g_\nu|^2 \sigma_{\eta,\nu}^2 + \sigma_D^2 . \quad (14)$$

With these effective parameters the standard iterative IDM detector can be applied. The basic principle of this detector is shown in Figure 3. After soft interference cancellation the resulting LLRs $L_\nu^{IC}[k]$ are deinterleaved. To exploit the fact that all relays transmitted an estimation of the same code bit b, the IDM-STC over the relays is interpreted as an additional repetition code in space domain. This means, to decode the Space-Time Code, denoted as STC^{-1} in Figure 3, all these deinterleaved LLRs denoted as $\Pi_\nu^{-1}(L_\nu^{IC}[k])$ are summed up before channel decoding

$$L_\Sigma[k'] = \sum_{\nu=1}^{N} \Pi_\nu^{-1}(L_\nu^{IC}[k']), \; k' = 1, \ldots, N_b . \quad (15)$$

$L_\Sigma[k']$ denotes these overall LLRs about the code bits $b[k']$ which are then fed to the decoder and afterwards reinterleaved. This operation is similar to Maximum Ratio Combining

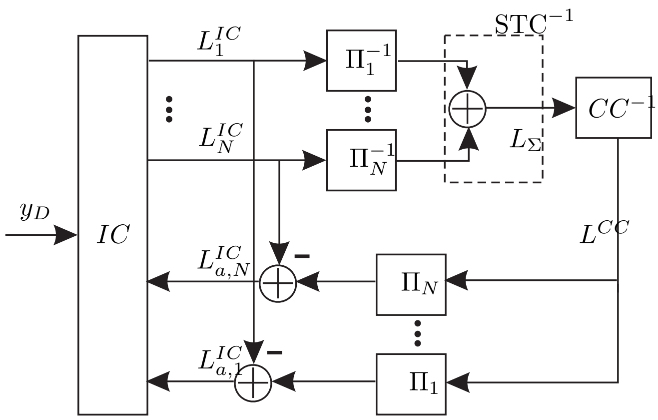

Fig. 3. Block diagram of the IDM-STC detector at the destination

(MRC). According to the principle of extrinsic information, the a-priori LLRs corresponding to relay R_ν are subtracted before the information $L_{a,\nu}^{IC}[k']$ is fed back to the interference canceler for the next iteration.

III. Simulation Results

Simululation results are shown in this Section in convolutional coded system. The different relay protocols in II-B are compared for different numbers of relays. The relays

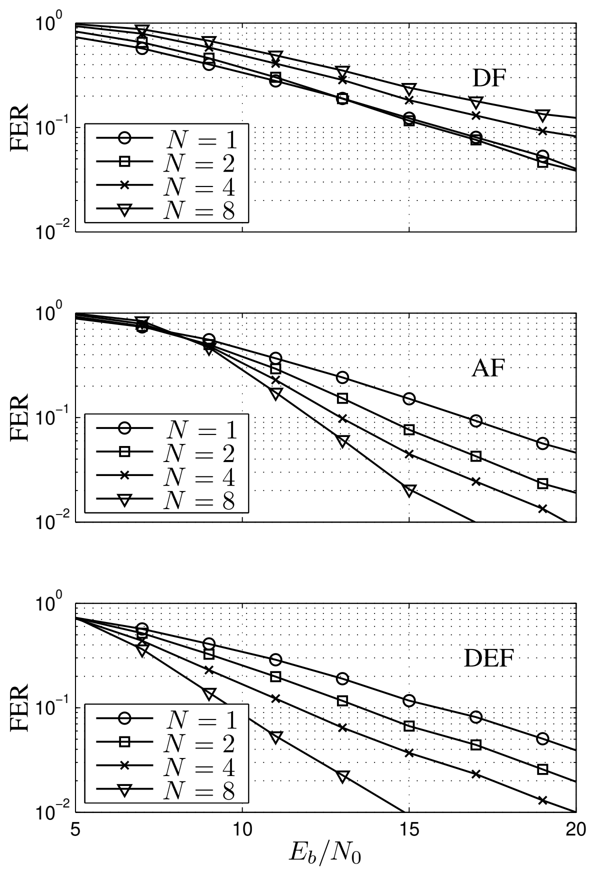

Fig. 4. Frame Error Rate vs. E_b/N_0 with 1, 2, 4 and 8 relays for different relay protocols, both hops flat Rayleigh fading, $[5\ 7]_8$ convolutional code

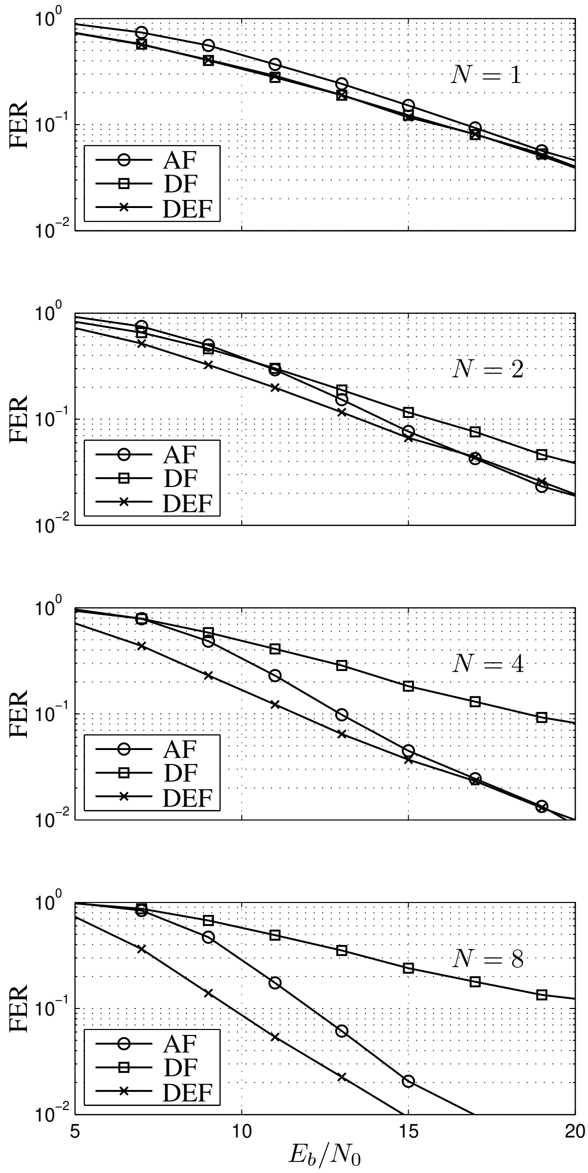

Fig. 5. Frame Error Rate vs. E_b/N_0 for different relay protocols with 1, 2, 4 and 8 relays, both hops Rayleigh fading, $[5\ 7]_8$ convolutional code

are located in the middle between source and destination. In [3] error-free transmission from the source to the relays was assumed, however, this can not be ensured in wireless systems. To model a more realistic scenario, we consider flat block Rayleigh fading for all channels. There is no direct transmission from S to D and $N_u = 1000$ information bits are transmitted in each frame. Asynchronous transmission of the relays is assumed and the delays of the relays are chosen randomly for each block limited to 4 bit durations. A $[5\ 7]_8$ convolutional code is used and 10 iterations are done at the destination. As we want to focus on the diversity gain of relay systems and not on the SNR gain due to additional transmitters, the transmit power of each relay is normalized to $1/N$ so that the total transmit power of all relays is normalized to one. This can be incorporated in the derivations in Section II-B by considering a factor of $1/\sqrt{N}$

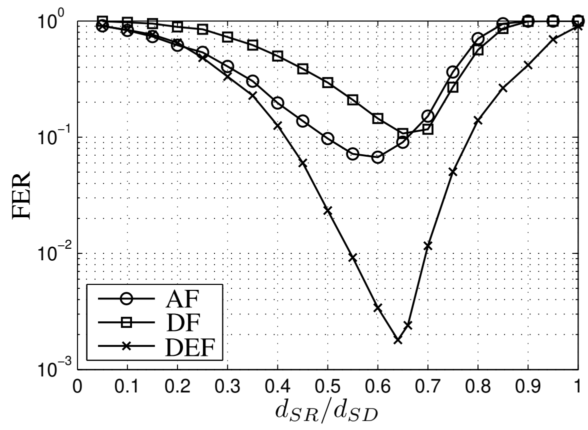

Fig. 6. Frame Error Rate vs. distance between Source and Relays for different relay protocols with 4 relays, first hop AWGN, second hop Rayleigh fading, $[5\ 7]_8$ convolutional code

at the output of all relays. In Figure 4 the frame error rates (FER) are shown for the different relay schemes described in Section II-B and different number of relays are used. It can be observed that fixed DF does not exploit the spatial diversity at all. This is due to the error propagation property of DF, the performance gets even worse for an increasing number of relays. In contrast to TDMA based transmission, for IDMA the errors of all relays are superimposed on the channel and limit the performance of the iterative detector. So relays with many errors increase the overall disturbance at the destination which limits the performance. AF exploits the diversity which is indicated by the steeper slope of the FER-curve in the case of several relays. The same is valid for DEF, but this scheme additionally exploits the coding gain at the relay yielding significant performance improvements. For direct comparisons of the three relay protocols, the same results are shown in a different arrangement in Figure 5. The advantage of DEF due to the coding gain gets obvious for all setups. DF performs well for 1 relay, but significantly degrades for more than 1. Asymptotically, AF performs similar to DEF, but in conclusion DEF turns out to be the best choice in all considered scenarios.

Now we consider a different system setup in order to emphasize the good performance of DEF in a wide range of scenarios. In a wireless network fixed relay stations will probably be positioned on roof tops. In the downlink this results in AWGN channels on the first hop. In Figure 6 the frame error rates for AF, DF and DEF are shown for this scenario versus the distance between source and relays. It is assumed that the relays are moved from the source to the destination, the path loss exponent is 3 and the number of relays is 4. Once more it can be seen that DEF clearly outperforms AF and DF in the whole range. The AWGN characteristic on the first hop leads to an improved performance when the relay is at $d_{SR}/d_{SD} = 0.65$ as the system is now limited by the second hop as it is bad with quite high probability. The advantage of DEF is even more pronounced here.

IV. Conclusions

In this paper the performance of Interleave-Division Multiplexing Space-Time Codes (IDM-STC) was investigated for different relay protocols in a fading environment. By applying IDM-STC, a very flexible relay network which is robust against asynchronism can be realized, but the specific constraints in relay networks like non-perfect decoding at the relays and limited cooperation have to be taken into account. The recently proposed Decode-Estimate-Forward (DEF) was applied to IDM-STC systems and was shown to be the best choice for all network setups. It clearly outperforms the other schemes as it exploits more diversity than DF and is superior to AF due to the coding gain. If the first hop has AWGN characteristic, the gain of DEF is even larger.

As the iterative detector can be simply extended to the multipath case, further research should investigate the considered IDM-STC with DEF in the case of frequency selective channels and also adaptive relay protocols should be applied.

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