Complexity Reduction Strategy for RAID in Multi-User Relay Systems

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***Abstract*—In this paper, distributed Interleave-Division-Multiplexing Space Time Codes (dIDM-STC) in Multi-User Decode-and-Forward Relay Systems are considered. Due to decoding errors at the relays, which are unavoidable in practical systems, error propagation to the destination occurs. In order to cope with this error propagation, recently a Reliability-Aware Iterative Detection Scheme (RAID) at the destination was proposed by the authors, which takes the decoding success at the relays, as well as the decoding reliability of the relays into account. This scheme requires a CRC check and also the estimation of the error probability at each relay. In this paper, a modification of RAID is presented, which only requires a CRC check at the relays, completely avoiding the estimation of the error probabilities at the relays and the signaling to the destination. Instead, the determination of the error probabilities is shifted to the destination reducing the complexity at the relays and the overall signaling overhead. As will be shown, the proposed complexity reduced RAID scheme (CR-RAID) allows for the same end-to-end performance in terms of frame-error-rates as the original RAID.**

I. INTRODUCTION

In the last decade, cooperative communications and especially relaying has been a promising and constantly growing field of research. Besides a reduction of pathlosses between communication nodes, relay systems also offer spatial diversity, allowing the application of diversity explotiting techniques known from Multiple Input Multiple Output (MIMO) systems as, e.g., Space-Time Coding (STC). STC has shown to be a very efficient transmit diversity exploiting strategy if no Channel State Information (CSI) is available at the transmitter [1], [2]. After introducing the concept of Virtual Antenna Arrays (VAAs), the first applications of STC in a distributed fashion were presented in [3], [4]. In [5] and [6] a STC approach based on the non-orthogonal multiple access scheme Interleave-Division Multiple Access (IDMA) [7] was presented. This Interleave-Division-Multiplexing Space-Time Code (IDM-STC) was applied to uncoded Decode-and-Forward (DF) systems in [8] where it was shown that IDM-STC is very suited for the application in distributed systems as it is very robust agains practical restrictions as imperfect synchronization among the transmitting nodes. In [9] distributed IDM-STC were applied to coded DF systems and it was pointed out that imperfect decoding at the relays should be taken into account for the detection at the destination as it leads to error propagation which can severely degrade the overall performance. Thus, in [10] and [11] the authors proposed a Reliability-Aware Iterative Detection Scheme (RAID) for distributed IDM-STC in relay systems which allows to incorporate the decoding success at the relays as well as the decoding reliability of the relays into the overall detection process at the destination. As was shown, RAID allows for a significantly better performance than the common detection scheme from [9] which neglects decoding errors at the relays. However, the main drawback of RAID compared to the common detection scheme is that it requires a CRC check at each relay, as well as the estimation of the error probabilities at the relays. Furthermore, this information has to be signaled to the destination. Thus, in this paper we propose a complexity reduction strategy for RAID, which completely avoids the estimation of the error probabilities at the relays. Instead, the determination of the error probabilities is shifted to the destination. The resulting complexity reduced RAID (CR-RAID) achieves the same performance as RAID, but only requires one CRC check per relay and frame and the signaling of the corresponding outcome to the destination, i.e., one bit per relay and frame.

The remainder of this paper is structured as follows. In Section II the system model is presented. In Section III the conventional RAID scheme is repeated briefly and a complexity reduction strategy is proposed. In Section IV some numerical results are given and in Section V finally a conclusion is drawn.

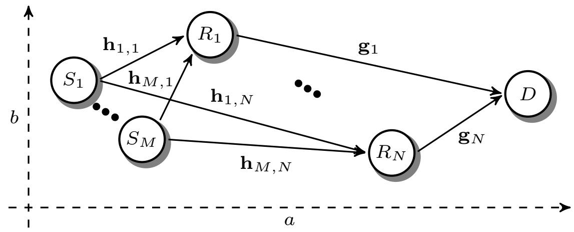

Fig. 1. Topology of the considered two-hop relay-system.

This work was supported in part by the German Research Foundation (DFG) under grant KA 841/20-2 and part of this work has been performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the European Union. The authors would like to acknowledge the contributions of their colleagues in METIS, although the views expressed are those of the authors and do not necessarily represent the project.

II. System Model

A. Overview

A two-hop relay system in which multiple sources $S_m,\ 1 \leq m \leq M$ transmit to one common destination D aided by multiple parallel relays $R_n,\ 1 \leq n \leq N$ as depicted in Fig. 1 is considered. No direct links between the sources and the destination are assumed. The channel impulse responses between S_m and R_n and between R_n and D are given by $\mathbf{h}_{m,n}$ and $\mathbf{g}_n$, respectively. All channels are statistically independent frequency-selective block Rayleigh fading with L i.i.d. channel taps. The path loss between any two nodes α and β is given by $d^{\epsilon}_{\alpha,\beta}$ where $d_{\alpha,\beta}$ denotes the distance between the corresponding nodes and ϵ is the path loss exponent. Furthermore, each receiving node experiences complex-valued additive white gaussian noise (AWGN) $\mathbf{n}$ of power σ^2_{n}. Due to the half-duplex constraint, the transmission time can be divided into two transmission phases. In the *Multiple Access Phase*, the sources simultaneously broadcast their information to the relays and in the *Broadcast Phase*, the relays simultaneously forward the processed information to the destination.

B. Multiple Access Phase

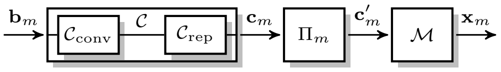

Fig. 2. Block diagram of source S_m.

In the multiple access phase, the sources broadcast their information simultaneously to all relays by applying IDMA [7]. Fig. 2 depicts the structure of source S_m. The binary information word $\mathbf{b}_m \in \mathbb{F}_2^{L_{\mathrm{b}}}$ of length L_{b} is encoded by a channel code $\mathcal{C}$ of rate R_{c} consisting of a serial concatenation of a convolutional code $\mathcal{C}_{\mathrm{conv}}$ of rate $R_{\mathrm{c,conv}}$ and a repetition code $\mathcal{C}_{\mathrm{rep}}$ of rate $R_{\mathrm{c,rep}}$. The binary codeword $\mathbf{c}_m \in \mathbb{F}_2^{L_{\mathrm{c}}}$ of length $L_{\mathrm{c}} = {}^{L_{\mathrm{b}}}/_{R_{\mathrm{c}}}$ is then interleaved by a user specific interleaver Π_m resulting in the interleaved code sequence $\mathbf{c}'_m$. Finally, the codeword is mapped to a sequence of symbols $\mathbf{x}_m \in \mathcal{A}^{L_{\mathrm{x}}}$ from an alphabet $\mathcal{A}$ with power $\sigma^2_{\mathrm{x}} = 1$ and broadcast to all relays.

The received signal $\mathbf{y}_n$ at relay R_n is given as the superposition of all source signals $\mathbf{x}_m$ and additive white gaussian noise $\mathbf{n}_n \in \mathbb{C}^{L_{\mathrm{x}}+L-1}$ of power σ^2_{n} as

$$\mathbf{y}_n = \sum_{m=1}^{M} \mathbf{H}_{m,n}\mathbf{x}_m + \mathbf{n}_n\,, \tag{1}$$

where $\mathbf{H}_{m,n}$ is the convolutional matrix of $\mathbf{h}_{m,n}$.

In Fig. 3 the structure of relay R_n is depicted. First, in order to separate the user signals $\mathbf{x}_m$, IDMA multi-user detection (MUD) is performed using the iterative soft-RAKE algorithm [7]. The MUD at relay R_n delivers Log-Likelihood-Ratios (LLRs) $\mathbf{\Lambda}^n_{\mathrm{b}_m}$ for the user information sequence $\mathbf{b}_m$. After hard decision, the estimates $\mathcal{Q}(\mathbf{\Lambda}^n_{\mathrm{b}_m})$ form the relay information sequence $\mathbf{b}_{m,n} = \mathcal{Q}(\mathbf{\Lambda}^n_{\mathrm{b}_m})$ where $\mathbf{b}_{m,n}$ denotes the information sequence at relay R_n with respect to S_m. Note, that due to decoding errors at the relay, the information words $\mathbf{b}_m$ and $\mathbf{b}_{m,n}$ might be different from each other. Hence, a CRC check is applied in order to determine the decoding success. The outcome of this CRC check is signaled to the destination where it is later on used by the new proposed detection scheme. However, independent of this outcome, the relay information sequences are encoded applying the same channel code $\mathcal{C}$ as the sources and interleaved by the same user specific interleavers Π_m. Furthermore, the interleaved sequences $\mathbf{c}'_{m,n}$ are interleaved again by a relay specific interleaver π_n such that a unique interleaver tuple $(\Pi_m;\pi_n)$ is assigned to each of the $M \cdot N$ double-interleaved sequences $\mathbf{c}''_{m,n}$ across all N relays. All sequences $\mathbf{c}''_{m,n}$ at R_n are mapped to symbols from the alphabet $\mathcal{A}$, superimposed and weighted by $\sqrt{\alpha_n} = \sqrt{1/M}$ such that the resulting relay signal $\mathbf{x}_n$ is normalized to power $\sigma^2_{x_n} = 1$ regardless of the number M of supported users.

C. Broadcast Phase

In the broadcast phase, the transmit signals $\mathbf{x}_n$ of all relays are broadcasted simultaneously to the destination D. Under the assumption of perfect decoding at all relays, each user signal is transmitted from all N relays and, hence, a distributed IDM-STC is formed across the N relays, comparable to [6]. The receive signal $\mathbf{y}$ at the destination consists of the superposition of all relay signals $\mathbf{x}_n$ convolved with the corresponding channel impulse responses $\mathbf{g}_n$ plus additive white gaussian noise $\mathbf{n} \in \mathbb{C}^{L_{\mathrm{x}}+L-1}$ of power σ^2_{n} as

$$\mathbf{y} = \sum_{n=1}^{N} \mathbf{G}_n\mathbf{x}_n + \mathbf{n}\,, \tag{2}$$

where $\mathbf{G}_n$ is the convolutional matrix of $\mathbf{g}_n$. At the destination, RAID is applied in order to obtain hard estimates $\hat{\mathbf{b}}_m$ for the user information $\mathbf{b}_m$ from the received signal $\mathbf{y}$.

III. Complexity Reduction Strategy for RAID

In this section, first the conventional RAID scheme is repeated briefly. For a detailed discussion refer to [10] and [11]. Then, a complexity reduction technique is proposed which is mainly based on shifting complexity from the relays to the destination and, thus, reducing the overall signaling overhead. In order to focus on the generall idea of the technique, only one arbitrary user is considered and the user index m is dropped for the remainder of this Section.

A. Conventional RAID

The main idea behind RAID is to introduce a grouping of relays into those relays which could decode correctly and those which could not. While the correct relays are processed jointly during the iterative detection, all erroneous relays are processed separately. Finally, after the iterative process, the information from the erroneous relays is weighted according to the bit error probability at the corresponding relay and subsequently the information from the correct as well as from the erroneous relays is combined into a final estimate. In order to perform the grouping and weighting, each relay performs a CRC check and an estimation of the bit error probability w.r.t. every detected frame as [12]

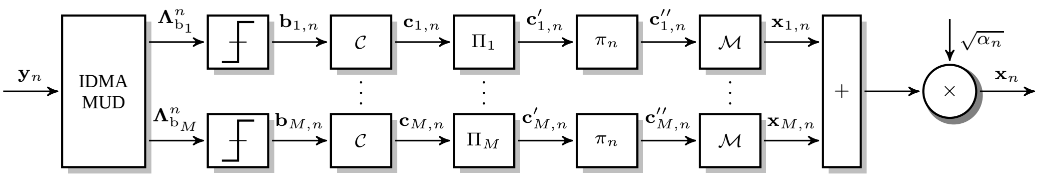

Fig. 3. Block diagramm of Relay R_n.

$$\hat{q}_n = \mathrm{E}\left\{\frac{1}{1+e^{|\boldsymbol{\Lambda}_{\mathrm{b}}^n|}}\right\} \approx \frac{1}{L_{\mathrm{b}}}\sum_{i=1}^{L_{\mathrm{b}}}\frac{1}{1+e^{|\Lambda_{\mathrm{b},i}^n|}}\,, \tag{3}$$

where $\hat{q}_n$ is the estimated bit error probability of the estimate $\mathbf{b}_n = \mathcal{Q}(\boldsymbol{\Lambda}_{\mathrm{b}}^n)$ of user information word $\mathbf{b}$ at relay R_n. In case of correct decoding of $\mathbf{b}$ at R_n, i.e. correct CRC check, ACK is signaled to the destination. In case of erroneous decoding, a NAK in form of the estimated bit error probability $\hat{q}_n$ is signaled to the destination. At the destination, first a MUD w.r.t. all relay information words $\mathbf{b}_n$ is performed. During this MUD the relay signals are grouped according to the CRC checks at the relays. Specifically, the signals from the correct relays are combined and detected jointly, whereas the signals from the erroneous relays are all detected separately. Afterwards, the soft estimates $\boldsymbol{\Lambda}_{\mathrm{b}_n}$ for all N relay information words describing $\mathbf{b}$ are weighted using the estimated error probabilities $\hat{q}_n$ from the relays and combined leading to a final estimate $\hat{\mathbf{b}}$ for $\mathbf{b}$. The structure of the RAID detector is depicted in Fig. 4. In the figure it is assumed without loss of generality that relays 1 up to $\kappa - 1$ decoded correctly while relays κ up to N decoded incorrectly. For a much more detailed description of RAID refer to [10] and [11].

Although RAID was shown to achive a significantly better performance than the conventional DF detection (cDF) from [9] it requires additional processing at the relays and additional signaling. Specifically, for each frame and relay a CRC check and the estimation of the error probability have to be performed and both have to be signaled to the destination. In order to reduce the added complexity, we propose a shift of the estimation of the error probabilities at the relays completely to the destination, reducing the required signaling for the proposed complexity reduced RAID scheme (CR-RAID) solely to the outcome of the CRC check, i.e., one bit per relay and frame.

B. Complexity Reduced RAID (CR-RAID)

The following explanations are based on Fig. 5 in which the relations between the different information words are depicted. The underlying assumption here is that due to the interleaving operations at source and relays all information bits are statistically independent from each other and are detected erroneously with the same probability. This assumption justifies a description of the correlation between any two information words $\mathbf{b}_1$ and $\mathbf{b}_2$ based on binary symmetric channels with error or crossover probability q as $\mathbf{b}_2 = \mathrm{BSC}(\mathbf{b}_1, q)$ or $\mathbf{b}_1 = \mathrm{BSC}(\mathbf{b}_2, q)$ similar to [13], [14].

On the left hand side of the figure, the source information word $\mathbf{b}$ is depicted. This information word is processed and

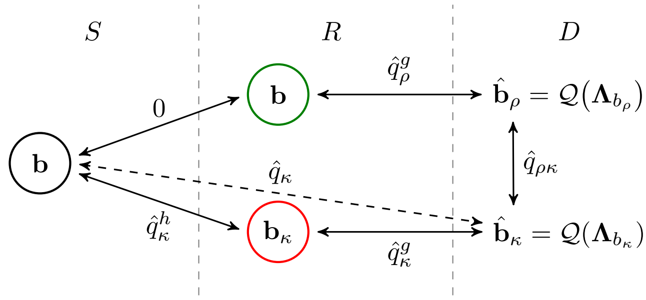

Fig. 5. BSC modelling based correlations between source information word $\mathbf{b}$, relay information word $\mathbf{b}_\rho$ of a correct relay, relay information word $\mathbf{b}_\kappa$ of an erroneous relay and their estimates $\hat{\mathbf{b}}_\rho$ and $\hat{\mathbf{b}}_\kappa$ at the destination.

transmitted as described in the previous Section. At the relays a hard decision is performed. For simplicity reasons, we focus on all correctly decoded relays with relay information word $\mathbf{b}$ (upper branch) and one arbitrary erroneously decoded relay with information word $\mathbf{b}_\kappa \neq \mathbf{b}$ (lower branch). The corresponding error probabilities are denoted at the arrows, i.e., 0 for the correct relays in the upper branch and $\hat{q}_\kappa^h$ for the erroneous relay in the lower branch. The relay information words are again processed and transmitted to the destination in the second phase, leading to the joint hard estimate $\hat{\mathbf{b}}_\rho$ for the correct relays and the hard estimate $\hat{\mathbf{b}}_\kappa$ for the erroneous relay. The error probabilities $\hat{q}_\rho^g$ and $\hat{q}_\kappa^g$ between the relay information words and the corresponding hard estimates at the destination are again denoted at the arrows. Furthermore, the correlation between the hard estimate of the information from the correct relays $\hat{\mathbf{b}}_\rho$ and the hard estimate of the information from the erroneous relay $\hat{\mathbf{b}}_\kappa$ is given as $\hat{q}_{\rho\kappa}$.

In order to perform the weighting for RAID, the error probability $\hat{q}_\kappa$ of the estimate $\hat{\mathbf{b}}_\kappa$ with respect to the source information word $\mathbf{b}$ (dashed line in Fig. 5) is required. Applying the rule of total probabilities [15] for the lower branch in the figure, it can be calculated as

$$\hat{q}_\kappa = P(b \neq \hat{b}_\kappa) \tag{4a}$$
$$= P(b \neq b_\kappa)P(b_\kappa = \hat{b}_\kappa) + P(b = b_\kappa)P(b_\kappa \neq \hat{b}_\kappa) \tag{4b}$$
$$= \hat{q}_\kappa^h\,(1 - \hat{q}_\kappa^g) + (1 - \hat{q}_\kappa^h)\,\hat{q}_\kappa^g\,, \tag{4c}$$

where b is one arbitrary element of $\mathbf{b}$. Since the error probability for the first hop transmission $\hat{q}_\kappa^h$ is not estimated at R_κ for CR-RAID, it is not available at the destination and, thus, (4c) can not directly be calculated. However, as can be seen from Fig. 5, following the upper branch, $\hat{q}_\kappa$ is also given as

$$\hat{q}_\kappa = \hat{q}_\rho^g\,(1 - \hat{q}_{\rho\kappa}) + (1 - \hat{q}_\rho^g)\,\hat{q}_{\rho\kappa}\,, \tag{5}$$

where the fact is exploited that the source information $\mathbf{b}$ was correctly estimated at the correct relays. Eq. (5) does not

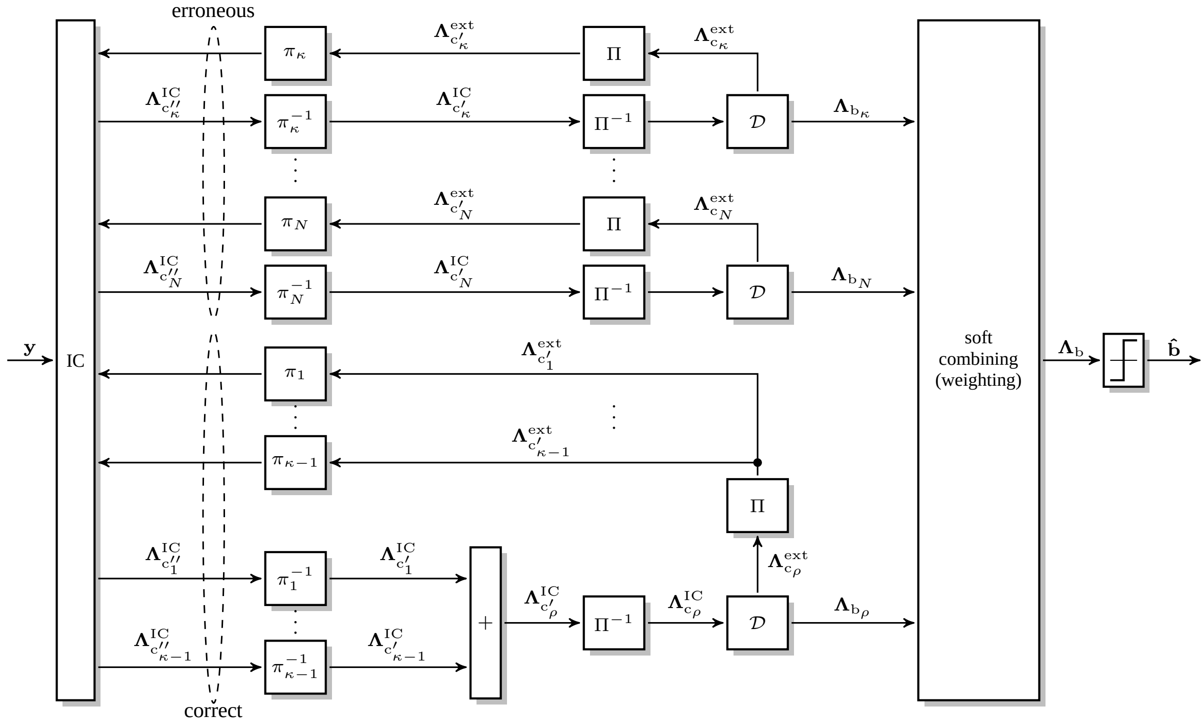

Fig. 4. Structure of the RAID scheme for dIDM-STC consisting of a relay grouping into correct and erroneous relays and a weighted combining. Here, relays R_1 up to $R_{\kappa-1}$ decoded correctly and relays R_κ up to R_N decoded erroneously.

require knowledge of the first hop transmission as the error probability for the correct relays is known to be zero from the corresponding CRC checks. Hence, in order to obtain the desired $\hat{q}_\kappa$, only the error probabilities $\hat{q}^g_\rho$ and $\hat{q}_{\rho\kappa}$ have to be determined.

1) Estimation of $\hat{q}^g_\rho$: The error probability $\hat{q}^g_\rho$ of $\hat{\mathbf{b}}_\rho$ with respect to the source information word $\mathbf{b}$ can directly be obtained from the LLRs $\boldsymbol{\Lambda}_{\mathrm{b}_\rho}$ after the iterative detection process similar to (3) as

$$\hat{q}^g_\rho \approx \frac{1}{L_\mathrm{b}} \sum_{i=1}^{L_\mathrm{b}} \frac{1}{1+e^{|\Lambda_{\mathrm{b}_{\rho,i}}|}} \,. \tag{6}$$

where L_b is the number of information bits per frame.

2) Estimation of $\hat{q}_{\rho\kappa}$: Again, by applying the law of total probabilities, the correlation $\hat{q}_{\rho\kappa}$ between $\hat{\mathbf{b}}_\rho$ and $\hat{\mathbf{b}}_\kappa$ is given by

$$\begin{aligned}\hat{q}_{\rho\kappa} &= \frac{1}{L_\mathrm{b}} \sum_{i=1}^{L_\mathrm{b}} P(b_{\rho,i} \neq b_{\kappa,i}) \\ &= \frac{1}{L_\mathrm{b}} \sum_{i=1}^{L_\mathrm{b}} \left[P(b_{\rho,i}=0)\, P(b_{\kappa,i}=1)\right. \\ &\quad \left. + P(b_{\rho,i}=1)\, P(b_{\kappa,i}=0)\right] . \end{aligned} \tag{7}$$

By expressing the probabilities as LLRs [16]

$$P(b=0|y) = \frac{e^{\Lambda_\mathrm{b}}}{1+e^{\Lambda_\mathrm{b}}} \tag{8a}$$

$$P(b=1|y) = \frac{1}{1+e^{\Lambda_\mathrm{b}}} \,, \tag{8b}$$

the correlation between the estimates $\hat{\mathbf{b}}_\rho$ and $\hat{\mathbf{b}}_\kappa$ is found to be

$$\hat{q}_{\rho\kappa} = \frac{1}{L_\mathrm{b}} \sum_{i=1}^{L_\mathrm{b}} \frac{e^{\Lambda_{\mathrm{b}_{\rho,i}}} + e^{\Lambda_{\mathrm{b}_{\kappa,i}}}}{(1+e^{\Lambda_{\mathrm{b}_{\rho,i}}})\,(1+e^{\Lambda_{\mathrm{b}_{\kappa,i}}})} \,. \tag{9}$$

3) Overall error probability for erroneous relays: Inserting $\hat{q}^g_\rho$ and $\hat{q}_{\rho\kappa}$ into (5), finally yields the desired overall error probability $\hat{q}_\kappa$ between $\mathbf{b}$ and $\hat{\mathbf{b}}_\kappa$. It is now used for the weighting identical to the conventional RAID in [10] as

$$\boldsymbol{\Lambda}^\kappa_\mathrm{b} = \log\left(\frac{e^{\boldsymbol{\Lambda}_{\mathrm{b}_\kappa}/2}\,(1-\hat{q}_\kappa) + e^{-\boldsymbol{\Lambda}_{\mathrm{b}_\kappa}/2}\,\hat{q}_\kappa}{e^{-\boldsymbol{\Lambda}_{\mathrm{b}_\kappa}/2}\,(1-\hat{q}_\kappa) + e^{\boldsymbol{\Lambda}_{\mathrm{b}_\kappa}/2}\,\hat{q}_\kappa}\right) . \tag{10}$$

The above described procedure is performed for every erroneous relay R_n. In the given example in Fig. 4 this is $n = \kappa$, .., N. Since all channels are statistically independent, the estimates from the correct relays $\boldsymbol{\Lambda}_{\mathrm{b}_\rho}$ as well as the weighted estimates from the erroneous relays $\boldsymbol{\Lambda}^n_\mathrm{b}$ can be summed up resulting in the final estimate

$$\boldsymbol{\Lambda}_\mathrm{b} = \boldsymbol{\Lambda}_{\mathrm{b}_\rho} + \sum_{n=\kappa}^{N} \boldsymbol{\Lambda}^n_\mathrm{b} \,. \tag{11}$$

In case of erroneous decoding at all relays, the above method fails as no correct relay for reference is available. In this case, a majority decision is performed, i.e.,

$$\boldsymbol{\Lambda}_\mathrm{b} = \sum_{n=1}^{N} \boldsymbol{\Lambda}_{\mathrm{b}_n} \,. \tag{12}$$

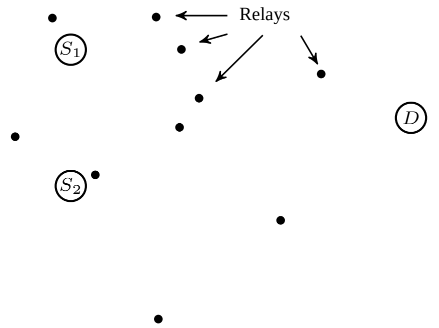

Fig. 6. Topology of the considered multi-user two-hop relay-system with $M = 2$ users and each black dot representing one of $N = 10$ randomly placed but fixed relays.

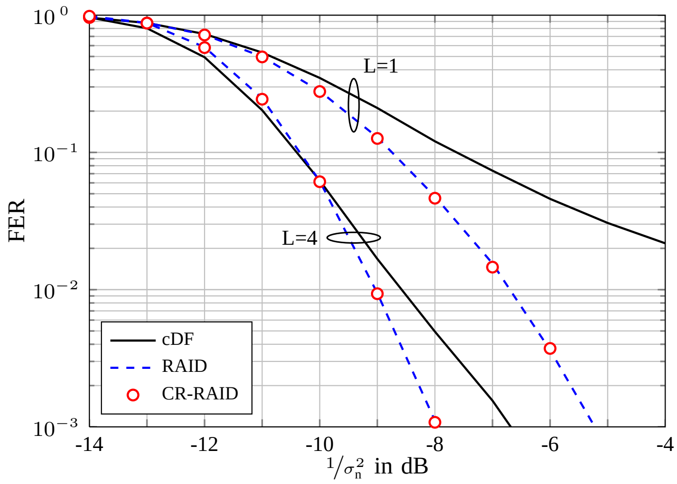

Fig. 7. FERs at the destination for common DF (cDF), original RAID and complexity reduced RAID (CR-RAID) for $L = 1$ and $L = 4$ channel taps. $M = 2$ users, $N = 10$ relays, $R_{\text{c,rep}} = {}^1/_{10}$.

IV. Numerical Results

A two-hop relay system with $M = 2$ users and $N = 10$ randomly placed but fixed relays as depicted in Fig. 6 is considered. Frequency-selective block Rayleigh fading channels with L channel taps are assumed on both hops and the path-loss exponent is set to $\epsilon = 3$. The code $\mathcal{C}$ consists of a serial concatenation of the $(5, 7)_8$ non-recursive convolutional code of rate $R_{\text{c,conv}} = {}^1/_2$ and a repetition code of rate $R_{\text{c,rep}} = {}^1/_{10}$. The codeword length is set to $L_c = 2000$ and a normalized QPSK modulation with $\sigma_x^2 = 1$ is applied. At the relays and at the destination $N_{\text{it}} = 10$ iterations are performed for detection.

As can be seen, the common DF scheme (cDF) clearly performs worse than both RAID schemes, since decoding errors at the relays are not considered for the detection at the destination. Only in the low SNR region for $L = 4$ cDF performs slightly better than RAID, as in this case the received power per layer is very low and a summation of all available information is better than a separated decoding as for RAID. However, as the received power increases RAID clearly outperforms cDF. Both RAID schemes, i.e., the original RAID scheme proposed in [10] [11] and CR-RAID proposed in this paper achieve the same performance in terms of frame-error-rates for frequency flat as well as for frequency selective channels.

V. Conclusion

In this paper, a complexity reduction strategy for the recently proposed reliability-aware iterative detection scheme (RAID) for distributed IDM-STC in multi-user relay systems has been proposed. The main idea behind this strategy is to shift the estimation of the error probabilities at the relays to the destination and, thus, avoiding signaling of the estimates from relays to destination. The resulting complexity reduced RAID scheme (CR-RAID) only requires signaling of one bit per frame and relay. However, despite the significantly reduced signaling overhead, the same performance in terms of frame-error-rates as for the original RAID scheme can be achieved.

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