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► **To cite this version:**

Haifa Fares Jridi, Charlotte Langlais. Iterative Joint Source-Relay Channel Decoding for the Noisy Decode-and-Forward Protocol. VTC 2013 Fall: IEEE 78th Vehicular Technology Conference, Sep 2013, Las Vegas, United States. <hal-00946909>

HAL Id: hal-00946909

<https://hal.science/hal-00946909v1>

Submitted on 23 May 2024

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Iterative Joint Source-Relay Channel Decoding for the Noisy Decode-and-Forward Protocol

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Abstract—In cooperative networks, despite its simplicity, the decode-and-forward protocol suffers from the problem of error propagation when the source-relay channel is noisy. By forwarding erroneous decoded messages, the relay significantly degrades the diversity order of the system. One trivial solution was to restrict the use of decode-and-forward protocol to reliable source-relay transmissions. However, the forwarded messages from the relay can be seen as data correlated with that transmitted by the source. This property can be exploited in order to alleviate the error propagation phenomenon. The problem of joint decoding of correlated sources is then directly transposed to the relay network. In this paper, we propose to exploit the potential correlation existing between the source and the relay messages in order to achieve enhanced end-to-end performance. Performance comparison with classical decoding of the decode-and-forward protocol is conducted especially under degraded source-relay channel conditions. We derive an analytical upper bound on the probability of error at the destination, which is verified by simulation results.

I. INTRODUCTION

The simplest cooperative scheme is the relay channel, introduced by van der Meulen in [1], where a source communicates with a single destination with the help of a relay, which assists the source by forwarding extra information to the destination. This forwarding can be performed in several ways. Among them, the decode-and-forward (DF) protocol [2] is very popular due to its simplicity and good performance in the case of successful decoding at the relay. However, when the relay fails to correctly decode the received message, the DF protocol is not beneficial. Indeed, for a noisy source-relay channel, the residual errors at the relay side are propagated, which will degrade the error correction capability at the destination. The inferior decoding performance of the relay node is likely to dominate the overall performance. This is typically manifested as an error floor on the bit error performance [3]. Therefore, the cooperative systems based in decode-and-forward have been proposed under the assumption of error-free or reliable source-relay channels. Previous works have discussed solutions to combat this effect as enumerated in [4]. In order to mitigate this error propagation phenomenon, we propose in this paper to apply the iterative joint decoding of correlated sources to the relay network. Similarly to the classical DF protocol, the relay detects all the information sent by the source before forwarding it to the destination.

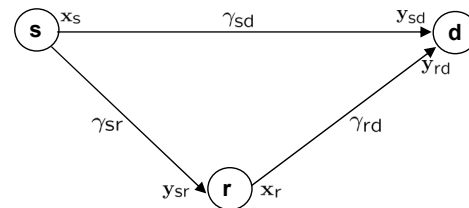


Fig. 1. Relay network consisting of one source with a common destination and one relay.

An iterative joint source-relay decoder is considered. It will iteratively decode, estimate and exploit the correlation between the source and the relay nodes based on the incoming messages from the two different channels (e.g., direct link and relay-destination link). This decoding setup is inspired from the joint decoding of correlated sources as described in [5] and stated in [6] for the noisy decode-and-forward scheme. However, two main differences are noted: **First, there is no distributed turbo code, the only turbo processing gain is related to the iterative decoding of the source and the relay messages. Second, in [6], it is stated that the source-relay channel quality has to be conveyed to the destination so that the probability of error on the source-relay channel can be computed.** In this paper, correlation amount, which also depends on the source-relay channel quality, is rather estimated dynamically in the iterative joint source-relay decoding process. Thus, no extra side information is transmitted. Therefore, this approach combines the advantages of decode-and-forward and compress-and-forward (CF), jointly mitigating both the effects of noise in the source-relay link and the propagation of decoding errors introduced by the relay node. The proposed scheme does not then exhibit an error floor like in the classical decoding of the decode-and-forward protocol. Moreover, the proposed protocol differs from the CF one by the fact that no quantization or compression operations is performed.

The outline of the paper is as follows. Section II introduces the system model. In Section III, we describe the iterative joint source-relay decoder. Section IV deals with the bound on the probability of error. In Section V, numerical results are presented and various comparisons are provided. Finally, conclusions are drawn in Section VI.

II. SYSTEM MODEL

This paper assumes a single relay for simplification as depicted in Fig. 1: source s communicates with destination d with the help of relay r , which uses the DF protocol. Moreover, the relay is assumed to operate in half-duplex mode, because this greatly simplifies practical implementation. We assume Time Division Duplex (TDD) operation in the rest of this paper. We restrict ourselves to BPSK modulation. The BPSK modulated symbol of a bit x_i is written as $\tilde{x}_i \in \{-1, 1\}$, and we use the BPSK mapping $0 \rightarrow +1, 1 \rightarrow -1$. The source node employs a binary linear code \mathcal{C} of length N and rate R . The encoder \mathcal{E} maps binary information words \mathbf{u}_s of length K to codewords \mathbf{x}_s .

Due to the broadcast nature of the wireless channel, both the destination and the relay receive a noisy observation of $\tilde{\mathbf{x}}_s$, denoted by \mathbf{y}_{sd} and \mathbf{y}_{sr} , respectively. The relay performs a hard decoding of \mathbf{y}_{sr} and generates \mathbf{x}_r , the estimate of the transmitted codeword \mathbf{x}_s , which can be viewed as a re-encoding process. Contrary to [6], no interleaving is used. This was justified in [5], where authors have not observed any interleaving gain if the data generated by one of the correlated sources is interleaved relative to the other one. The extrinsic information generated cannot then be better than that provided from the knowledge of the source correlation only. Note that the relay may not be able to decode \mathbf{y}_{sr} correctly, and therefore \mathbf{x}_s and \mathbf{x}_r may differ. However, \mathbf{x}_r is still a valid codeword from the code \mathcal{C} of a transmitted message denoted by \mathbf{u}_r . Based on the two noisy observations \mathbf{y}_{sd} and \mathbf{y}_{rd} , the destination estimates the transmitted message \mathbf{u}_s ; this estimate is denoted $\hat{\mathbf{u}}_s$.

The source-destination, the source-relay and the relay-destination signal-to-noise ratios (SNRs) denoted, respectively, by γ_{sd} , γ_{sr} and γ_{rd} , are assumed to be known only at the receiver side. The receiver observations are described as

$$\begin{aligned} \mathbf{y}_{sd} &= \mathbf{h}_{sd}\tilde{\mathbf{x}}_s + \mathbf{w}_{sd} \\ \mathbf{y}_{sr} &= \mathbf{h}_{sr}\tilde{\mathbf{x}}_s + \mathbf{w}_{sr} \\ \mathbf{y}_{rd} &= \mathbf{h}_{rd}\tilde{\mathbf{x}}_r + \mathbf{w}_{rd} \end{aligned} \quad (1)$$

Here \mathbf{w}_{sd} , \mathbf{w}_{sr} and \mathbf{w}_{rd} are additive white Gaussian noise (AWGN) variables with zero-mean and respective variance σ_{sd}^2 , σ_{sr}^2 and σ_{rd}^2 , and \mathbf{h}_{sd} , \mathbf{h}_{sr} and \mathbf{h}_{rd} denote the source-destination, source-relay and relay-destination channel coefficients, respectively. Two different channel models are considered: binary-input AWGN ($\mathbf{h}_{sd} = \mathbf{h}_{sr} = \mathbf{h}_{rd} = 1$) and Rayleigh fading. In the fading case, each coefficient is a Rayleigh distributed, unit-variance random variable. We distinguish two different fading channels: the block fading channel where the channel coefficients are assumed to be constant over the transmission of the whole message, in this particular scenario temporal diversity is limited; and the fast fading channel where the channel coefficients change for each transmitted symbol. The SNRs for the source-destination, source-relay and relay-destination links are given by $\gamma_{sd} = 1/(2\sigma_{sd}^2)$, $\gamma_{sr} = 1/(2\sigma_{sr}^2)$ and $\gamma_{rd} = 1/(2\sigma_{rd}^2)$, respectively. Based on

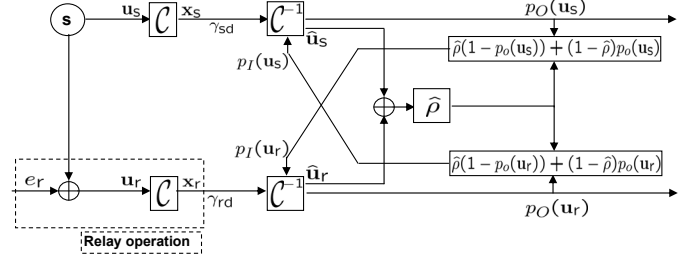


Fig. 2. Iterative source-controlled decoding scheme for the relay channel.

this model, the destination computes the L-values

$$L_{sd,i} = 4\gamma_{sd}\mathbf{y}_{sd}[i] \quad (2)$$

$i = 1, 2, \dots, N$, where $\mathbf{y}[i]$ denotes the i -th element of vector \mathbf{y} .

III. ITERATIVE JOINT SOURCE-RELAY CHANNEL DECODING

In this section, we apply the iterative joint channel decoding scheme of correlated sources to the DF protocol of a relay network. Unlike the CF protocol, we assume that the source as well as the relay do not make use of source coding, but only channel coding. At the destination, an iterative decoder is used to exploit the source/relay correlation. As the relay is forwarding the estimated message transmitted from the source, a certain correlation is observed between the two binary messages arriving to the destination. By taking into account this correlation, we alleviate the performance degradation due to the error propagation proper to the DF protocol. The correlation amount depends on the source-relay channel quality. The empirical cross-correlation between \mathbf{u}_s and \mathbf{u}_r is defined as $\hat{\rho} = \frac{w(\mathbf{u}_s \oplus \mathbf{u}_r)}{K} = \frac{w(\mathbf{e}_r)}{K}$, where $w(\cdot)$ is the Hamming weight of the argument and \mathbf{e}_r is a relay error vector. The empirical cross-correlation can be rewritten as $\hat{\rho} = p(\mathbf{u}_s[i] = \mathbf{u}_r[i])$, $i = 1, 2, \dots, K$, where $\mathbf{u}[i]$ denotes the i -th element of vector \mathbf{u} . Consequently, the empirical cross-correlation can be given by $\hat{\rho} = 1 - p_{e_r}^b$, where $p_{e_r}^b$ is the bit error probability over the source-relay channel. Note that with this definition, the source-relay channel quality is a tuning parameter of the empirical cross-correlation between the source and the relay messages.

A. Iterative Decoder

Given the noisy observation sequences \mathbf{y}_{sd} and \mathbf{y}_{rd} , the joint maximum likelihood probability (MAP) decoding problem can be given by

$$\begin{aligned} [\hat{\mathbf{u}}_s, \hat{\mathbf{u}}_r] &= \underset{[\mathbf{u}_s, \mathbf{u}_r]}{\operatorname{argmax}} p(\mathbf{u}_s, \mathbf{u}_r | \mathbf{y}_{sd}, \mathbf{y}_{rd}) \\ &= \underset{[\mathbf{u}_s, \mathbf{u}_r]}{\operatorname{argmax}} p(\mathbf{y}_{sd} | \mathbf{u}_s) p(\mathbf{y}_{rd} | \mathbf{u}_r) p(\mathbf{u}_s, \mathbf{u}_r) \end{aligned} \quad (3)$$

The first equality is equivalent to that adopted in [7]. The second equality in the last expression is obtained using Bayes rule, and the third term explicitly takes into account source/relay correlation. By neglecting any constant term and

$$\begin{aligned}
p_e^b &\leq \sum_{d=d_{\min}}^{\infty} w_d p_d(\mathbf{u}_s, \mathbf{u}_e) \\
&\leq \frac{1}{2} \sum_{d=d_{\min}}^{\infty} w_d \sum_{w=1}^{w_e} \operatorname{erfc} \left(\sqrt{Rd\gamma_{\text{sd}}} + \frac{\tilde{L}_a(w_e - 2w)}{4\sqrt{Rd\gamma_{\text{sd}}}} \right) \binom{w_e}{w} (1 - p_{e_r}^b(\gamma_{\text{sr}}))^{(w_e-w)} (p_{e_r}^b(\gamma_{\text{sr}}))^w
\end{aligned} \tag{4}$$

by using the total probability theorem, the joint decoding problem can be split into two low complexity sub-problems:

$$\begin{aligned}
\hat{\mathbf{u}}_s &= \operatorname{argmax}_{\mathbf{u}_s = \mathcal{C}^{-1}(\mathbf{x}_s)} p(\mathbf{y}_{\text{sd}}|\mathbf{x}_s)p(\mathbf{u}_s|\hat{\mathbf{u}}_r) \\
\hat{\mathbf{u}}_r &= \operatorname{argmax}_{\mathbf{u}_r = \mathcal{C}^{-1}(\mathbf{x}_r)} p(\mathbf{y}_{\text{rd}}|\mathbf{x}_r)p(\mathbf{u}_r|\hat{\mathbf{u}}_s)
\end{aligned} \tag{5}$$

Thanks to this new problem's formulation, the decoder does not take explicitly into account the erroneous decisions made at the relay. This is included implicitly in the amount of correlation observed between source and relay messages arriving at the destination.

As depicted in Fig. 2, each decoder detects its corresponding information message based on the *a priori* information given by the other decoder. As in a traditional turbo decoding, a soft input soft output (SISO) decoder is straightforwardly required, operating at the symbol level based on MAP decoding algorithm [8]. We denote by $p_O(\mathbf{u}_s)$ and $p_O(\mathbf{u}_r)$, namely the *a posteriori* probabilities, the estimations produced by the two SISO decoders, and by $p_I(\mathbf{u}_s)$ and $p_I(\mathbf{u}_r)$ the *a priori* probabilities at the decoders inputs. According to the correlation model, the *a posteriori* probabilities evaluated at the j -th iteration are converted into *a priori* probabilities for the $(j+1)$ -th iteration, as stated in Fig. 2.

B. Estimation of the Correlation

We assume that the source-relay channel quality measure is not available at the destination side. Thus, since the correlation amount is directly related to this quality measure, it is necessary to estimate the parameter ρ in each one of the decoding iterations. The estimate value of ρ , $\hat{\rho}$, can be obtained as

$$\begin{aligned}
\hat{\rho} &= \frac{1}{K} \sum_{i=1}^K p_O(\mathbf{u}_s[i] = 0)p_O(\mathbf{u}_r[i] = 0) \\
&\quad + p_O(\mathbf{u}_s[i] = 1)p_O(\mathbf{u}_r[i] = 1)
\end{aligned} \tag{6}$$

Note that from noisy received vectors, the empirical cross-correlation $\hat{\rho}$ is not exactly the true value ρ , but the deviation remains relatively small even for the first iteration. Successive iterations ensure an improved cross-correlation estimate, as it has been verified by simulations.

IV. BOUND ON THE ERROR PROBABILITY

We are interested in evaluating the performance of the iterative joint source-relay channel decoding scheme for a noisy Gaussian relay channel. To this aim, we consider the simplified problem defined in (5). Without loss of generality,

we focus on the first decoder. The error events at the relay and at the destination are defined, respectively, by

$$e_r := \{\mathbf{u}_r \neq \mathbf{u}_s\}, \quad e := \{\hat{\mathbf{u}}_s \neq \mathbf{u}_s\} \tag{7}$$

For the analysis, we assume that the all-zero message is transmitted, i.e., $\mathbf{u}_s = 0$ ($\mathbf{x}_s = 0$). This implies no loss of generality as we consider that \mathcal{C} is a linear code. Using its corresponding decoding rule, the error event at the destination corresponds to the decoding of \mathbf{x}_e , which differs from \mathbf{x}_s , the codeword transmitted by the source. Consequently, the error event is given by

$$\begin{aligned}
e &\equiv \{\exists \mathbf{x}_e = \mathcal{C}(\mathbf{u}_e) \in \mathcal{C} \setminus \{0\} : \\
&\quad p(\mathbf{y}_{\text{sd}}|\mathbf{x}_s)p(\mathbf{u}_s|\hat{\mathbf{u}}_r) < p(\mathbf{y}_{\text{sd}}|\mathbf{x}_e)p(\mathbf{u}_e|\hat{\mathbf{u}}_r)\}
\end{aligned} \tag{8}$$

Using L-values, this error event can equivalently be rewritten as

$$e \equiv \left\{ \exists \mathbf{x}_e \in \mathcal{C} \setminus 0 : \sum_{i \in \mathcal{S}(\mathbf{x}_e)} L_{\text{sd},i} < \ln \frac{p(\mathbf{u}_e|\hat{\mathbf{u}}_r)}{p(\mathbf{u}_s|\hat{\mathbf{u}}_r)} \right\} \tag{9}$$

where $\mathcal{S}(\mathbf{x})$ is the support of the vector \mathbf{x} , defined as $\mathcal{S}(\mathbf{x}) = \{i : x_i \neq 0\}$; notice that $|\mathcal{S}(\mathbf{x})| = w(\mathbf{x})$. The pairwise error probability conditioned to $\hat{\mathbf{u}}_r$ has been formulated in [9] and is given by

$$p_d(\mathbf{u}_s, \mathbf{u}_e|\hat{\mathbf{u}}_r) = \frac{1}{2} \operatorname{erfc} \left(\sqrt{Rd\gamma_{\text{sd}}} + \frac{\tilde{L}_a(w_e - 2w)}{4\sqrt{Rd\gamma_{\text{sd}}}} \right) \tag{10}$$

where w is the weight of the estimated information message $\hat{\mathbf{u}}_r$, w_e is the weight of the information message \mathbf{u}_e , d is the weight of codeword \mathbf{x}_e and $\tilde{L}_a = \ln \left(\frac{\hat{\rho}}{1-\hat{\rho}} \right) = \ln \left(\frac{1-p_{e_r}^b(\gamma_{\text{sr}})}{p_{e_r}^b(\gamma_{\text{sr}})} \right)$. Note that as $\hat{\mathbf{u}}_r$ is equal to 1 with the probability $p_{e_r}^b$ and is equal to 0 with the probability $1 - p_{e_r}^b$, w is then binomially distributed and consequently the average pairwise error probability is given by

$$\begin{aligned}
p_d(\mathbf{u}_s, \mathbf{u}_e) &= \frac{1}{2} \sum_{w=1}^{w_e} \operatorname{erfc} \left(\sqrt{Rd\gamma_{\text{sd}}} + \frac{\tilde{L}_a(w_e - 2w)}{4\sqrt{Rd\gamma_{\text{sd}}}} \right) \\
&\quad \binom{w_e}{w} (1 - p_{e_r}^b(\gamma_{\text{sr}}))^{(w_e-w)} (p_{e_r}^b(\gamma_{\text{sr}}))^w
\end{aligned} \tag{11}$$

Using the union bound property, the upper bound on the bit error probability is given in (4) for the particular case of Gaussian channels. Note that n_d is the number of codewords of distance d and w_d is the cumulative Hamming weight (for information bits) of all codewords of weight d . Thus, w_e is approximated by the average information weight per codeword

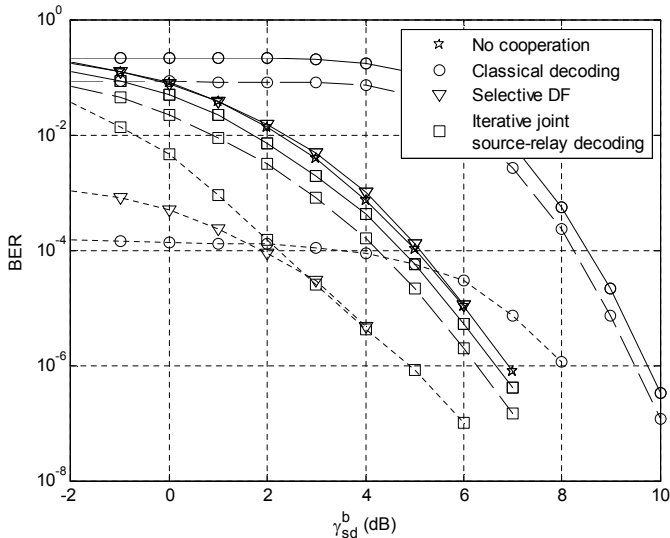


Fig. 3. Bit error probability bounds (lines) and BER simulation results (markers) of the DF protocol with iterative joint source-relay channel decoding vs. BER simulation results of the DF protocol with classical decoding over Gaussian channels for $\gamma_{rd}^b = 5$ dB: Solid lines for $\gamma_{sr}^b = -3$ dB, dashed lines for $\gamma_{sr}^b = 0$ dB and dotted lines for $\gamma_{sr}^b = 5$ dB.

equal to w_d/n_d . Furthermore, $p_{e_r}^b$ can be approximated by its tight upper bound given by

$$p_{e_r}^b \approx \frac{1}{2} \sum_{d=d_{min}}^{\infty} \text{erfc} \left(\sqrt{Rd\gamma_{sr}^b} \right) \quad (12)$$

V. NUMERICAL RESULTS AND COMPARISONS

In this section, we give bit error rate (BER) results of the iterative joint source-relay channel decoding of the DF protocol and compare them with those of the classical channel decoding of the DF protocol, for various channel models and conditions. We also illustrate the tightness of the error probability bound derived in Section IV in the case of Gaussian channels by comparing it to simulation results (BER). For the examples here we considered the rate-1/2 convolutional encoder with generator polynomials (05,07) in octal form for \mathcal{C} , and the information message length is $K = 128$ bits.

The BER performance of the iterative joint source-relay channel decoding vs. the classical channel decoding over Gaussian channels are reported in Fig. 3. In particular, we plot the analytical bounds on the bit error probability of the the joint iterative source-relay channel decoding of the DF protocol (lines) together with the simulation results (markers), as a function of γ_{sd}^b for several values of γ_{sr}^b and a fixed value of $\gamma_{rd}^b = 5$ dB, where $\gamma^b = \gamma/R$, R being the rate of the code. A good match between the simulations and the bounds is observed. Performance simulation results of the classical decoding setup are given for the same channel conditions using both the original and the selective DF protocols for comparison purposes. The selective DF protocol is taking into account the relay contribution only when successful decoding is performed at the relay node, otherwise, a non cooperative transmission is

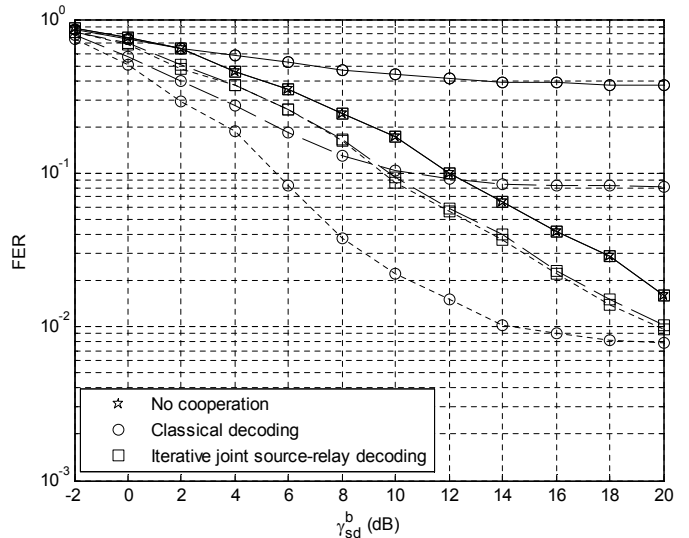


Fig. 4. FER simulations of the DF protocol with iterative joint source-relay channel decoding vs. FER simulations of the DF protocol with classical decoding over block fading Rayleigh channels and for $\gamma_{rd}^b = \gamma_{sd}^b$: error floor phenomenon illustration. Solid lines for $\gamma_{sr}^b = 0$ dB, dashed lines for $\gamma_{sr}^b = 10$ dB and dotted lines for $\gamma_{sr}^b = 20$ dB.

performed. The BER performance curves of classical decoding using the selective DF protocol are situated between curves of original DF and those of non cooperative scheme. From this figure, a significant performance degradation is observed for the classical decoding of the DF protocol with respect to the non-cooperative scheme and the selective DF protocol, when source-relay channel is poor (-3 to 0 dB). This phenomenon is avoided by performing the iterative joint source-relay channel decoding at the destination side. Even for a very bad source-relay channel, this cooperative scheme outperforms both the non-cooperative transmission and the selective DF protocol, since the information arriving from the relay is considered as a side information, and relay errors are implicitly taken into account in the decoding process at the destination node. On the other hand, when a good source-relay channel is considered ($\gamma_{sr}^b = 5$ dB), the classical decoding of the original/selective DF protocol performs better than the joint iterative source-relay channel decoding for relatively bad source-destination channel ($\gamma_{sd}^b < 2$ dB).

Fig. 4 gives an illustration of the error propagation phenomenon of the DF protocol for a noisy source-relay transmission. Frame error rate (FER) curves are given for different values of γ_{sr}^b as a function of $\gamma_{sd}^b = \gamma_{rd}^b$, over a block fading Rayleigh channel. The well-known result of error propagation is clearly visible for $\gamma_{sr}^b = 0$ dB or 10 dB. Classical decoding of the DF protocol does not provide any diversity but has an error floor, which is higher than 10^{-2} . This error floor is totally determined by the source-relay channel SNR [10]. However, when the proposed decoding system is carried out, it always outperforms the non-cooperative case even for noisy source-relay transmission. Notice that in the case of reliable source-relay transmission ($\gamma_{sr}^b = 20$ dB), the classical decoding of the DF protocol is performing even better than the proposed

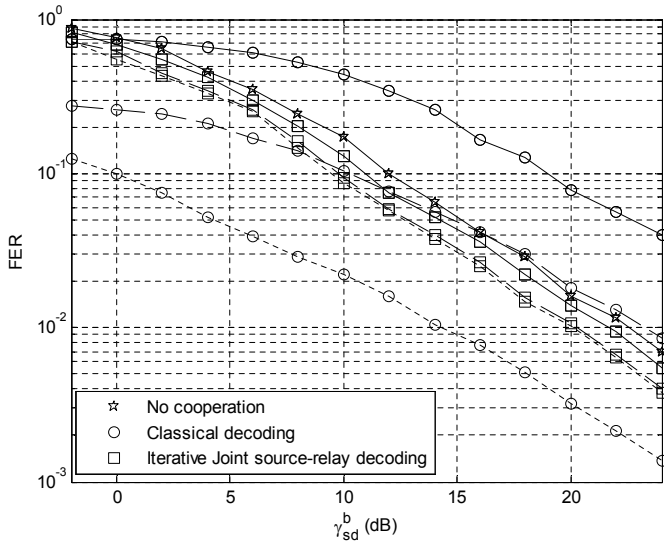


Fig. 5. FER simulations of the DF protocol iterative joint source-relay channel decoding vs. FER simulations of the DF protocol with classical decoding over **block fading Rayleigh channels** and for $\gamma_{rd}^b = 10$ dB: solid lines for $\gamma_{sr}^b = 0$ dB, dashed lines for $\gamma_{sr}^b = 10$ dB and dotted lines for $\gamma_{sr}^b = 20$ dB.

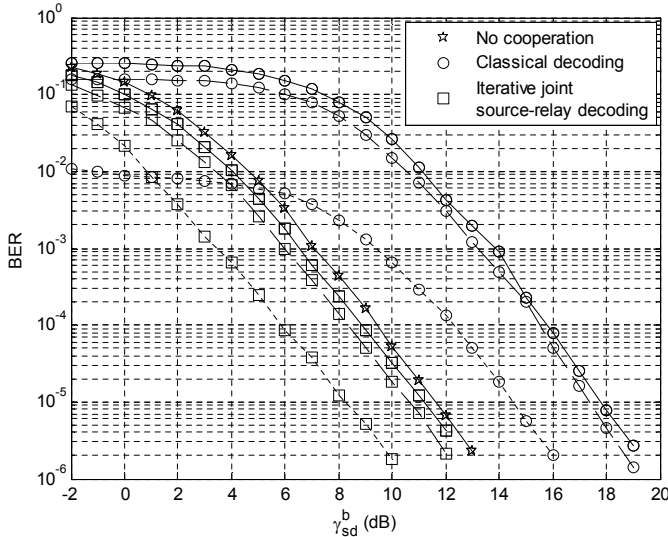


Fig. 6. BER simulations of the DF protocol iterative joint source-relay channel decoding vs. BER simulations of the DF protocol with classical decoding over **fast fading Rayleigh channels** and for $\gamma_{rd}^b = 5$ dB: solid lines for $\gamma_{sr}^b = -3$ dB, dashed lines for $\gamma_{sr}^b = 0$ dB and dotted lines for $\gamma_{sr}^b = 5$ dB.

decoding setup. Indeed, it is preferred to take into account explicitly the relay contribution as a direct alternative to ensure diversity gain. Thus, the classical decoding is more beneficial than the iterative joint source-relay decoding, where only the source/relay correlation amount is used in order to obtain further coding gain.

In Fig. 5, we plot FER simulations of the classical decoding scheme vs. those of the proposed scheme over block fading Rayleigh channel as a function of γ_{sd}^b (in dB) for several values of γ_{sr}^b and a fixed value of $\gamma_{rd}^b = 10$ dB. For

bad source-relay channel quality, the iterative joint source-relay decoding of the DF protocol performs at least as the non cooperative scheme. Therefore, contrary to the classical decoding of the DF protocol, no performance degradation is observed, so that the error floor effect in Fig. 4 can be alleviated. However, this gain vanishes for high source-relay SNR (i.e., high correlation). In this case, the classical decoding of the DF protocol is preferred.

Fig. 6 shows the performance improvement that is achieved by the use of the iterative joint source-relay channel decoding with respect to the classical decoding for fast fading Rayleigh channels. In this figure, we plot BER simulations as a function of γ_{sd}^b for several values of γ_{sr}^b and a fixed value of $\gamma_{rd}^b = 5$ dB. From this figure, same conclusions can be conducted as from Fig. 3. Here, we show that the improvements of the BER performance brought by using the iterative joint source-relay channel decoding setup are still visible for the case of fast fading Rayleigh channel.

VI. CONCLUSIONS

In this work, we have applied the joint decoding scheme of two correlated sources to the DF protocol of a relay network, leading to the joint iterative source-relay decoding scheme. Significant improvements were observed with respect to the classical decoding of the DF protocol and the non-cooperative scheme, especially for noisy source-relay transmissions. Results were given for many channel models and conditions. Furthermore, we derived an analytical bound on the bit error probability of this proposed decoding scheme, in order to approve simulation results. Several extensions of the results published in this paper could be considered as topics for further investigation, for instance the extension to multiple relays.

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