Energy-aware Design of Inter-Relay Cooperation for Distributed Relaying Networks

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***Abstract*—We consider distributed relaying networks using space-time block codes (STBC) to exploit cooperative diversity. In order to mitigate the impact of error propagation for Decode-Forward (DF), an inter-relay cooperation (IRC) scheme is proposed that allows message exchanges between the relays based on punctured channel codes. Specifically, one of the error-free relays broadcasts punctured bits as side information to help failed relays to re-decode. Consequently, only relays capable of successful decoding transmit to the destination using STBC. Furthermore, an energy model for relays is introduced, so that the proposed IRC scheme can be evaluated with respect to throughput and energy consumptions for transmission, baseband and RF circuit at all relays. Simulation results show the superior performance using IRC, which should be properly designed under the influence of energy considerations.**

I. Introduction

Cooperative networks supported by relaying nodes bring in diversity gains that effectively combat fading in wireless communications [1]. For a distributed relaying system with multiple relaying nodes using Decode-Forward (DF), several cooperation strategies have been proposed in the literature in order to exploit the spatially distributed nature of the relays. Laneman *et al.* analyzed the outage probability for cooperative diversity protocols in [2], where based on cyclic redundancy codes (CRC), only the relays that decode the source message correctly ("correct relays") transmit to the destination using STBC. When all relays have decoding errors ("erroneous relays"), the destination only uses the message received directly from the source. It was also demonstrated, that the diversity degree depends on the number of cooperating terminals, but not on the number of error-free relays. Note that the relays involved in the transmission have to be well synchronized due to their distributed nature in the network, which requires extra overhead [3]. A simple solution is to select only one relay to transmit, e.g., Nosratinia *et al.* investigated a relay selection method [4], [5] in which only the correct relay with the highest signal-to-noise ratio (SNR) on the relay-destination link transmits to the destination.

In this paper we assume that the source-destination link is not available in distributed relaying networks using DF for simplicity. If all relays have decoding errors, the relays can switch to Amplify-Forward (AF), but this is not considered here. Otherwise only correct relays are active for transmission using orthogonal STBC. In order to increase the number of correct relays, one of the correct relays broadcast side information in the form of punctured bits to help the erroneous relays to re-decode. Since such information exchange termed inter-relay cooperation (IRC) requires extra time and energy cost for transmission, baseband and RF circuit, a throughput-based analysis with respect to the total energy consumption at the relays is used for performance evaluation.

The remainder of this paper is organized as follows. The distributed relaying system is described in Section II. Inter-relay cooperation is introduced in Section III and the design method based on punctured channel codes is illustrated in detail. Section IV discusses the energy model at the relays. Performance evaluations using throughput analysis with respect to energy consumption are presented in Section V and Section VI concludes this paper.

II. Distributed Relaying System without IRC

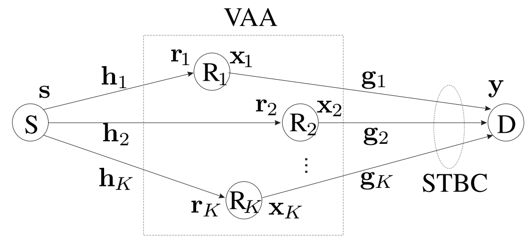

Fig. 1. Distributed relaying system with K relays constituting a VAA. In case of no IRC, all relays participate in the transmission to D using STBC.

We consider a distributed relaying system where one source S communicates with one destination D supported by K relays R_k, $1 \leq k \leq K$, as shown in Fig. 1. The relays constitute a virtual antenna array (VAA) and operate in half-duplex mode. Assuming a fixed network structure, each relay R_k knows its own index k. All involved nodes are equipped with a single antenna. Additionally, coded Orthogonal Frequency Division Multiplexing (OFDM) transmissions are assumed for the source-relay and relay-destination links. At S the encoded and interleaved code bit vector $\mathbf{c}$ with code rate R_{C} is mapped to N_{FFT} symbols using M-QAM modulation, where N_{FFT} indicates the number of subcarriers. Denoting the transmit symbol on subcarrier m by s_m, the receive signal r_m on subcarrier $1 \leq m \leq N_{\mathrm{FFT}}$ at R_k is given by

$$r_{k,m} = h_{k,m} s_m + n_{k,m} \ . \tag{1}$$

Upon receiving the signal vector $\mathbf{r}_k = [r_{k,1} \cdots r_{k,N_{\text{FFT}}}]^T$, relay R_k estimates the source message by decoding and re-encoding and transmits the symbol vector $\mathbf{x}_k = [x_{k,1} \cdots x_{k,N_{\text{FFT}}}]^T$ to D in the second phase using an orthogonal STBC. This yields the receive signal y_m on subcarrier m at destination D

$$y_m = \sum_{k=1}^{K} g_{k,m} x_{k,m} + q_m \ . \tag{2}$$

The receive signal vector $\mathbf{y} = [y_1 \cdots y_{N_{\text{FFT}}}]^T$ is STBC decoded at the destination, followed by channel decoding to recover the source message. Note that STBC with $K > 2$ leads to a rate loss R_{STBC} [6], which is compensated by adapting the channel code rate of the RD link to $R_{\text{C,RD}} > R_{\text{C}}$ for rate matching, such that $R_{\text{STBC}} R_{\text{C,RD}} = R_{\text{C}}$ holds. The transmit power at S and the VAA are denoted as $\mathcal{P}_{\text{S}}$ and $\mathcal{P}_{\text{R}}$, respectively. Furthermore, $\mathcal{P}_{\text{R}}$ is equally assigned to the active relays. The frequency selective channels are Rayleigh block fading containing N_{H} equal power channel taps in time domain. Correspondingly, $h_{k,m}$ and $g_{k,m}$ in (1) and (2) represent the channel coefficients in frequency domain with variance $\sigma_{\text{H}}^2 = 1/(N_{\text{H}} d^{\alpha})$, path-loss exponent α and distance components $d \in \{d_{\text{SR}}, d_{\text{RD}}\}$. The additive white Gaussian noise (AWGN) terms $n_{k,m}$ and q_m are i.i.d. zero-mean complex random variables with variance σ_n^2. It is assumed that the relays are close to each other, i.e., $d_{\text{IRC}} \ll d$ with d_{IRC} denoting the distance between the relays.

III. IRC BASED ON PUNCTURED CHANNEL CODES

In the system model described in Fig. 1, the relays transmit the estimated source message using STBC to exploit spatial diversity. However, if there are relays that failed to decode the message correctly, these decoding errors will be forwarded to the destination. Note that even if only one relay decodes imperfectly, the erroneous OFDM symbol carrying decoding errors will superimpose correct symbols from other relays at the destination and thus degrades the overall performance.

In order to mitigate the impact of error propagation, inter-relay cooperation (IRC) is introduced in this paper that allows dedicated transmissions for data exchange between the relays within the VAA. To this end, the type and amount of exchanged information should be properly designed. In this paper, based on punctured channel codes, the source S encodes the information bits to a codeword of length n using a channel code with mother rate $R_{\text{C,mom}}$. Afterwards, n_{pun} bits are punctured, resulting in a shortened codeword of length $n_{\text{S}} = n - n_{\text{pun}}$ and code rate R_{C} for transmission, where $R_{\text{C}} > R_{\text{C,mom}}$ holds. After receiving and decoding, each relay R_k is aware of its own decoding status by exploiting a CRC code, which is assumed to detect errors perfectly with negligible overhead. The relays now inform each other about their decoding status by broadcasting a one-bit acknowledgement (ACK) or negative acknowledgement (NAK) denoted as CRC bit. Since each relay R_k knows its own index k, the CRC bits can be sent in a pre-fixed order, e.g., R_1 sends first and after receiving the CRC bit from R_k, relay R_{k+1} sends its CRC bit. Consequently, all relays are aware of the set $\mathcal{D}$ containing all correct relays. Depending on the cardinality $|\mathcal{D}|$ three events can be distinguished.

- **Event E_1:** $|\mathcal{D}| = K \rightarrow$ **all relays correct**
  Exchange of punctured bits is not necessary since all relays have already decoded successfully. Therefore, K relays transmit to D using STBC.
- **Event E_2:** $|\mathcal{D}| = 0 \ \rightarrow$ **all relays erroneous**
  No punctured bits are exchanged since they may not be generated correctly. Even though, still K relays transmit to D using STBC as this scenario is beyond discussion in our system setup.
- **Event E_3:** $1 \leq |\mathcal{D}| < K \rightarrow$ **some relays correct**
  One relay $R_\kappa \in \mathcal{D}$, e.g., the one with the smallest index $\kappa = \min\limits_{\text{R}_k \in \mathcal{D}} k$, re-generates and broadcasts $n_{\text{IRC}} \leq n_{\text{pun}}$ punctured bits. The erroneous relays combine the source message with these punctured bits for re-decoding. Subsequently, the erroneous relays broadcast their CRC status again to determine the new set $\mathcal{D}'$. Finally, the relays in $\mathcal{D}'$ transmit to destination D using STBC with rate matching introduced in Section II.

It should be emphasized that events E_1 and E_2 conform to the benchmark system without IRC. However, the proposed IRC scheme may increase the number of correct relays ($|\mathcal{D}'| \geq |\mathcal{D}|$) in E_3. Correspondingly, the system equation (2) for the VAA to D transmission on subcarrier m remains unchanged for E_1 and E_2 while it is adapted to

$$y_m = \sum_{k \in \mathcal{D}'} g_{k,m} x_{k,m} + q_m \tag{3}$$

for E_3. Note that $n_{\text{IRC}} \leq n_{\text{pun}}$ in E_3 indicates that it is not necessarily the case that all punctured bits are exchanged in the IRC phase. Less punctured bits exchange leads to smaller amount of overhead but results in worse re-decoding quality.

$\leftarrow T_{\text{OFDM}} \rightarrow$	$\leftarrow T_{\text{IRC}} \rightarrow$	$\leftarrow T_{\text{OFDM}} \rightarrow$
S $\rightarrow$ VAA	IRC	VAA $\rightarrow$ D

Fig. 2. Transmission protocol from S to D with the extension of IRC. T_{OFDM} denotes the time duration for one OFDM symbol. The extra time expense for IRC is denoted as T_{IRC}.

In this paper, a dedicated time slot is assigned for IRC, as shown in Fig. 2. In contrast to one OFDM symbol duration T_{OFDM}, T_s denotes one symbol duration for single-carrier transmission using M_{IRC}-QAM modulation in the IRC phase. Thus the total time required for IRC is

$$T_{\text{IRC}} = \begin{cases} K T_s & \text{if } \text{E}_1, \text{E}_2 \\ \left(2K - |\mathcal{D}| + \lceil \frac{n_{\text{IRC}}}{M_{\text{IRC}}} \rceil \right) T_s & \text{if } \text{E}_3 \end{cases} \tag{4}$$

and depends on the events. Note that each relay requires one individual symbol duration T_s to broadcast its CRC bit, leading to $K T_s$ to determine the set $\mathcal{D}$ in the VAA. In contrast, $(K - |\mathcal{D}|)\, T_s$ is required to determine $\mathcal{D}'$ since only the erroneous relays have to update and send their decoding status after re-decoding in event E_3. The time for the punctured bits exchange is calculated as $T_{\text{pun}} = \lceil \frac{n_{\text{IRC}}}{M_{\text{IRC}}} \rceil T_s$.

IV. ENERGY MODEL AT THE RELAYS

The benefit of IRC does not come for free. It requires extra processing which consumes battery energy. Therefore, we analyze the trade-off between data throughput and energy cost. To this end, energy model is needed for a fair evaluation. In this paper, we concentrate on the energy consumption at the relays, since the changes in energy consumption for the different events mainly occur at the relays.

For the IRC scheme, the energy at the relays during one OFDM transmission $\mathcal{E}_{\text{relay}}$ can be divided into the energy required to support the source-relay-destination transmission $\mathcal{E}_{\text{SRD}}$ and the energy dedicated to IRC $\mathcal{E}_{\text{IRC}}$, yielding

$$\mathcal{E}_{\text{relay}} = \mathcal{E}_{\text{SRD}} + \mathcal{E}_{\text{IRC}} \ . \tag{5}$$

The energy consumption for a wireless communication node consists of three parts: the RF circuit, the baseband processing and the transmit signal energy. The energy consumption at the relays can be further decomposed into

$$\mathcal{E}_{\text{SRD}} = \mathcal{E}_{\text{SRD,RF}} + \mathcal{E}_{\text{SRD,Base}} + \mathcal{E}_{\text{SRD,Signal}} \tag{6a}$$

$$\mathcal{E}_{\text{IRC}} = \mathcal{E}_{\text{IRC,RF}} + \mathcal{E}_{\text{IRC,Base}} + \mathcal{E}_{\text{IRC,Signal}} \ . \tag{6b}$$

The energy consumption of each component will be discussed in detail in the following subsections. Note that in general the baseband processing time must be shorter than the transmission time in order to avoid the accumulation of the receive signals. On the other hand, the active time of the transmitter and the receiver is always longer than the transmission time, because of the signal flow in the RF circuits. To simplify the energy evaluation, we assume that all these time components are equal to T_{OFDM} for the source-relay-destination transmission and T_{pun} for IRC, i.e.,

$$T_{\text{SRD,Tx}} = T_{\text{SRD,Rx}} = T_{\text{SRD,Base}} = T_{\text{OFDM}} \tag{7a}$$

$$T_{\text{IRC,Tx}} = T_{\text{IRC,Rx}} = T_{\text{IRC,Base}} = T_{\text{pun}} \ . \tag{7b}$$

A. Transmit Signal Energy

For a given receive SNR, the transmit signal power P_{R} for the RD transmission is related to the distance d_{RD}. Therefore, the influence of the transmit signal power P_{R} on the total power consumption depends on d_{RD}. In the next section, the throughput will be evaluated with respect to the total energy consumption at the relays for different d_{RD}. During IRC, remind that the relays within the VAA are assumed to be close to each other, i.e., $d_{\text{IRC}} \ll d_{\text{RD}}$ holds. Denoting $\mathcal{P}_{\text{IRC,Signal}}$ the transmit power for IRC with $\mathcal{P}_{\text{IRC,Signal}} = \mathcal{E}_{\text{IRC,Signal}}/T_{\text{pun}}$, yields

$$\frac{\mathcal{P}_{\text{IRC,Signal}}}{\mathcal{P}_{\text{R}}} \propto \left(\frac{d_{\text{IRC}}}{d_{\text{RD}}}\right)^{\alpha} \ll 1 \tag{8}$$

due to the path-loss effect. Thus, comparing to $\mathcal{P}_{\text{R}}$, the transmit signal power $\mathcal{P}_{\text{IRC,Signal}}$ for IRC can be reasonably neglected. Noticeably, $\mathcal{P}_{\text{R}}$ is constant regardless of the number of active relays K_{act} for the RD transmission after IRC.

B. RF Circuit Energy

Since among the three modes in a transceiver circuit, active, sleep and wake-up mode, the active mode consumes the most energy. only this mode is considered in this paper. In [7] a power model for RF circuit in the active mode specified for sensor networks is proposed, which is adapted here for analysis. For a given RF circuit, the circuit energy of most RF parts is generally assumed to be fix. The power consumption in one transmitter $\mathcal{P}_{\text{Tx}}$ and one receiver $\mathcal{P}_{\text{Rx}}$ is the summation of those fixed component, such as mixer, LNA and IFA, which are listed in Table I. However, the power consumption of the power amplifier $\mathcal{P}_{\text{PA}}$ is related to the transmit signal power $\mathcal{P}_{\text{R}}$ by $\mathcal{P}_{\text{PA}}/\mathcal{P}_{\text{R}} = \xi/\varrho - 1$, where $\varrho = 0.35$ is the drain efficiency and ξ is the PAPR. In this paper, the PAPR is approximately $\xi = 10 \cdot \log_{10} N_{\text{FFT}}$ dB [8] for an OFDM signal. The RF circuit energy for the RD transmission reads

$$\begin{aligned}\mathcal{E}_{\text{SRD,RF}} &= (K\mathcal{P}_{\text{Rx}} + K_{\text{act}}\mathcal{P}_{\text{Tx}} + \mathcal{P}_{\text{PA}}) \cdot T_{\text{OFDM}} \\ &= (K\mathcal{P}_{\text{Rx}} + K_{\text{act}}\mathcal{P}_{\text{Tx}} + (\xi/\varrho - 1)\mathcal{P}_{\text{R}}) \cdot T_{\text{OFDM}} \ .\end{aligned} \tag{9}$$

For the benchmark scheme without IRC, all relays are used for the RD transmission and thus K_{act} always equals K. On the other hand, for the scheme with IRC, K_{act} is varying and depends on the events. In case of event E_1 or E_2 all relays are used; where for event E_3, only the correct relays transmit to D, i.e. $K_{\text{act}} = |\mathcal{D}'|$.

Parameters	Values
circuit power of mixer	$\mathcal{P}_{\text{Mix}} = 30.3$ mW
circuit power of low noise amplifier	$\mathcal{P}_{\text{LNA}} = 20$ mW
circuit power of frequency synthesizer	$\mathcal{P}_{\text{Syn}} = 50$ mW
circuit power of intermediate frequency amplifier	$\mathcal{P}_{\text{IFA}} = 3$ mW
circuit power of filter	$\mathcal{P}_{\text{Fil}} = 2.5$ mW

TABLE I
RF PARAMETERS FOR SENSOR NETWORKS IN [7].

To evaluate the RF energy consumption for IRC $\mathcal{E}_{\text{IRC,RF}}$, the exchange of CRC status is neglected since for each OFDM symbol only one CRC bit needs to be exchanged per relay. As mentioned in Section III, only the one relay transmits the punctured bits to the erroneous relays for re-decoding. Thus, the extra energy consumption for reception and transmission for IRC is summarized as

$$\mathcal{E}_{\text{IRC,RF}} = (\mathcal{P}_{\text{Tx}} + (K - |\mathcal{D}|)\,\mathcal{P}_{\text{Rx}}) \cdot T_{\text{pun}} \ . \tag{10}$$

Since the transmission signal energy for IRC is neglected as mentioned in last subsection, $\mathcal{P}_{\text{PA}}$ can also be ignored in (10).

C. Baseband Processing Energy

The energy consumption in baseband processing is calculated at CMOS level, where a CMOS gate consumes dynamic energy (switching power and short-circuit current) and static energy (subthreshold leakage current, gate leakage current etc.). Since the dominating term in a ”well-designed” circuit is the switching component [9], in this paper the static energy consumption is neglected.

The switching energy is proportional to the effective capacity C_{eff} and the supply voltage V_{dd}. Denoting the effective switching factor by $0 \leq \beta \leq 1$ and the load capacity of one CMOS by C_{L}, the effective capacity is defined as $C_{\text{eff}} = \beta \cdot C_{\text{L}}$. Thus, the switching energy for a single CMOS is given by

$$\mathcal{E}_{\text{CMOS}} = \beta C_{\text{L}} V_{\text{dd}}^2 \quad . \tag{11}$$

Based on the energy model of one CMOS, the baseband energy for the RD transmission and IRC are defined as

$$\mathcal{E}_{\text{SRD,base}} = K N_{\text{SRD}} \mathcal{E}_{\text{CMOS}} \tag{12a}$$
$$\mathcal{E}_{\text{IRC,base}} = (K - |\mathcal{D}|) N_{\text{IRC}} \mathcal{E}_{\text{CMOS}} \ , \tag{12b}$$

respectively. Here N_{SRD} and N_{IRC} denote the number of CMOS gates required for the RD transmission and IRC. For RD transmission, the baseband energy captures the FFT, IFFT and the decoding block where the number of CMOS gates used for a 16-bit FFT and viterbi decoder is around 4.2×10^6 and 0.45×10^6 respectively, whereas for IRC it takes into account only the re-decoding block at the erroneous relays.

V. Performance Evaluation

A. Throughput Analysis

For a fair comparison of the schemes with and without IRC the throughput is analyzed taking the extra time consumption T_{IRC} into account. Since T_{IRC} is related to different events E_1, E_2 and E_3 by (4), the overall throughput η is given by

$$\eta = \sum_{i=1}^{3} \Pr\{\text{E}_i\} \frac{N_{\text{FFT}} \log_2 M \, R_{\text{C}}}{2T_{\text{OFDM}} + T_{\text{IRC},i}} (1 - \text{FER}_{\text{D},i}) \ , \tag{13}$$

where $T_{\text{IRC},i}$ and $\text{FER}_{\text{D},i}$ denote the time duration for IRC and the frame error rate (FER) at D in case of event E_i. $\Pr\{\text{E}_i\}$ is the probability of E_i depending on the decoding success of the relays. The throughput η represents the number of correct information bits received at D per unit time such that it captures the impact of extended time in case of IRC.

B. Parameter Settings

A relaying system with $K = 4$ relays using DF is considered. The relaying channels are assumed to be block Rayleigh fading with path-loss exponent $\alpha = 2.5$ and $N_{\text{H}} = 5$ multi-path taps. The receive SNRs at R and D are defined as $\text{SNR}_{\text{SR}} = \mathcal{P}_{\text{S}} / \left(\sigma_n^2 d_{\text{SR}}^{\alpha}\right)$ and $\text{SNR}_{\text{RD}} = \mathcal{P}_{\text{R}} / \left(\sigma_n^2 d_{\text{RD}}^{\alpha}\right)$. One OFDM symbol occupies $N_{\text{FFT}} = 256$ subcarriers with 16-QAM modulation. In case of IRC, the source uses rate-compatible punctured convolutional (RCPC) codes [10] with $R_{\text{C,mom}} = 1/3$, constraint length $L_{\text{C}} = 4$, generator polynomial $[13, 15, 11]_8$. By puncturing $n_{\text{pun}} = 512$ bits, the effective code rate $R_{\text{c}} = 1/2$ is achieved for transmission with $n_{\text{IRC}} = 512$ or 128 for IRC. The Viterbi algorithm is used for decoding. The VAA employs an orthogonal STBC of rate $R_{\text{STBC}} = 3/4$ [6] when $K_{\text{act}} = 3$ or 4 and $R_{\text{STBC}} = 1$ when $K_{\text{act}} = 2$. The relay simply unicasts to the destination when $K_{\text{act}} = 1$. The channel code rate used for the RD transmission is adapted to $R_{\text{C,RD}} = 2/3$ in case of using 3/4-STBC for rate matching. IRC is only subject to AWGN disturbance with 256-QAM modulation and $\text{SNR}_{\text{IRC}} = 30\,\text{dB}$ due to closely located relays. The bandwidth of all links is set to $W = 1\,\text{MHz}$, the background noise power density equals $N_0 = -174\,\text{dBm/Hz}$, and $\sigma_n^2 = N_0 W$ holds. We consider an equal power allocation between S and the VAA, i.e., $\mathcal{P}_{\text{S}} = \mathcal{P}_{\text{R}}$, and $\mathcal{P}_{\text{R}}$ is equally assigned to the active relays. The constituted VAA joints the direct line between S and D with $d_{\text{SR}} = d_{\text{RD}}$.

The energy consumption for baseband is calculated based on 90 nm CMOS processor [11]. The load capacity equals $C_{\text{L}} = 1$ fF and the effective switching factor β is set to 12.5% .

C. Simulation Results

For the relaying system with IRC the probability distributions for the number of correct relays before re-recoding $|\mathcal{D}|$ and after re-decoding $|\mathcal{D}'|$ are drawn in Fig. 3. As can be observed in a), event E_1 ($|\mathcal{D}| = 4$) occurs more likely at high SNR and vice versa for E_2 ($|\mathcal{D}| = 0$). Note that E_3 is the superposition of $|\mathcal{D}| \in \{1, 2, 3\}$ and occurs more likely at medium SNR. Fig. 3b) shows the probability for number of correct relays after re-decoding. The benefit of IRC is, that after re-decoding at the erroneous relays the number of correct relays may increase, as the probabilities for $|\mathcal{D}'| = 1$ decrease and increase for $|\mathcal{D}'| = 4$ over the whole SNR region comparing b) to a). Note that the probability distribution that all relays failed to decode (E_2) remains unchanged since no punctured bits are exchanged. Furthermore, the curves for 1, 2 and 3 correct relays after re-decoding totally vanish in case that all punctured bits are exchanged, as shown in c). This indicates that if at least one relay can decode successfully, all relays will be error-free after re-decoding when enough punctured bits are exchanged in our system setup.

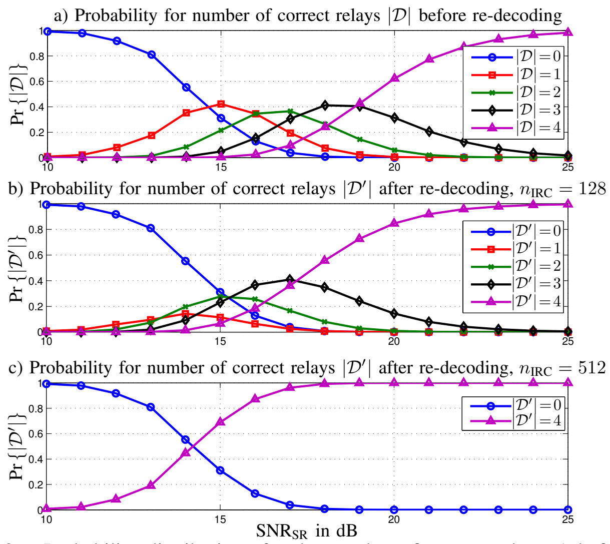

Fig. 3. Probability distributions for the number of correct relays a) before and b), c) after re-decoding with $n_{\text{IRC}} = 128, 512$ punctured bits exchange.

The IRC consumes additional energy. Fig. 4a) exhibits the total energy consumption for IRC defined in (6b) versus SNR_{SR}. E_3 occurs more often at medium SNR, which leads to an increased energy consumption for the relays. More exchanged punctured bits result in a higher energy consumption for $\mathcal{P}_{\text{IRC,RF}}$ because T_{pun} is related to the amount of

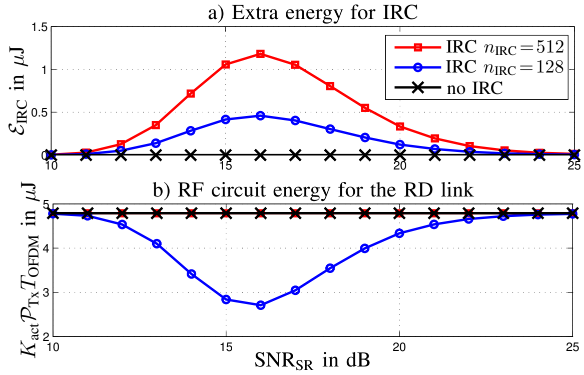

Fig. 4. a) Extra total energy consumption for IRC $\mathcal{E}_{\mathrm{IRC}}$. b) RF circuit energy consumption for the RD link $K_{\mathrm{act}}\mathcal{E}_{\mathrm{Tx}}$.

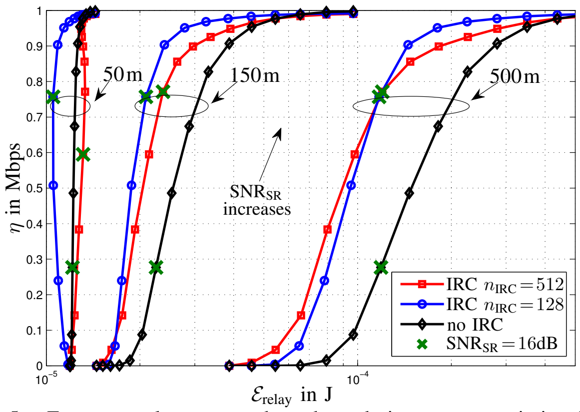

Fig. 5. Energy at relays versus throughput during one transmission from S to D for different distances and different number of exchanged bits in IRC.

exchanged punctured bits. Fig. 4b) shows the RF circuit energy $K_{\mathrm{act}}\mathcal{P}_{\mathrm{Tx}}T_{\mathrm{OFDM}}$ for the RD transmission versus $\mathrm{SNR}_{\mathrm{SR}}$. If only part of the punctured bits are exchanged in E_3, less energy is required because of a smaller number of active relays $K_{\mathrm{act}} \leq 4$, while exchanging all the punctured bits leads to a constant $K_{\mathrm{act}} = 4$ due to perfect re-decoding. This effect results in an increase in the total energy consumption at the relays for $n_{\mathrm{IRC}} = 512$ and a decrease for $n_{\mathrm{IRC}} = 128$ compared to the benchmark scheme without IRC. This indicates that the reduction of RF circuit energy for the RD transmission is more significant than the energy increase due to IRC.

Fig. 5 shows the throughput versus the total energy consumption at the relays for different SD distances. Note that the adjacent markers correspond to 1dB step on each curve. At $d_{\mathrm{SD}} = 500\mathrm{m}$, the transmit signal energy dominates the total energy at the relays. Since the IRC scheme mitigates the impact of error propagation, less transmit signal energy is required to reach the same throughput compared to the benchmark scheme without IRC. Particularly, $n_{\mathrm{IRC}} = 512$ leads to decreased throughput compared to $n_{\mathrm{IRC}} = 128$ in the high energy region, resulting in a crosspoint around $\mathrm{SNR}_{\mathrm{SR}} = 16\mathrm{dB}$ and indicating that less exchanged punctured bits preserve the FER performance at D but save time for IRC. As d_{SD} decreases, the transmit signal energy imposes less influence on the total energy consumption, which leads to an early-coming crosspoint, e.g., around $\mathrm{SNR}_{\mathrm{SR}} = 13\mathrm{dB}$ for $d_{\mathrm{SD}} = 150\mathrm{m}$. At $d_{\mathrm{SD}} = 50\mathrm{m}$ the RF circuit and baseband energy dominates the total energy at the relays. If all punctured bits are exchanged, the perfect re-decoding at erroneous relays in E_3 requires extra energy for IRC and the same RF circuit energy for the RD transmission. If only part of the punctured bits are exchanged, the extra energy for IRC and RF circuit energy is reduced. Thus only part of the punctured bits exchange improves the performance compared to the scheme without IRC while using all punctured bits has a counter effect, and no crosspoint is observed. These results show that the number of punctured bits should be carefully chosen, e.g., depending on the distance.

VI. Conclusion

In this paper an inter-relay cooperation (IRC) scheme is proposed based on punctured channel codes for distributed relaying systems employing STBC at the relays. After re-decoding with the help of punctured bits in the IRC phase, the number of correct relays may increase. For a fair evaluation an energy model for relays is constructed to perform a throughput-based analysis with respect to energy consumptions at the relays. Simulation results exhibit the superior performance using IRC under proper amount of exchanged punctured bits.

VII. Acknowledgement

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