Joint Channel-and-Network Coding Using EXIT Chart Aided Relay Activation

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***Abstract*—This paper presents a relay activation scheme designed for joint channel-and-network (JCN) coded systems relying on an iterative decoding. A primary focus is on proposing criteria of the relay activation to find the best user combination for cooperative relaying, which exploits extrinsic information transfer (EXIT) chart analysis. We will demonstrate that the EXIT chart aided relay activation scheme is capable of reducing the probability of outages, despite increasing the effective throughput of network.**

***Index Terms*—User cooperation, network coding, channel coding, iterative decoding, multi-hop, cooperative relaying, EXIT chart analysis.**

I. Introduction

User cooperation has attracted significant research attention owing to its spatial diversity benefits [1], [2]. Relaying or multi-hop transmissions constitute the simplest form of user cooperation. However, due to the creation of the broadcast and cooperation phases, they achieve a high diversity gain at the cost of a factor two multiplexing loss. To overcome this deficiency, the adoption of network coding has been studied, where we multiplex several users' information by their algebraic superposition over a finite field [3], [4]. As a benefit of the network coding, the above-mentioned half duplex multiplexing loss is mitigated without sacrificing the diversity gain. The designs of joint channel-and-network (JCN) codes and their iterative detection have been investigated in [5]–[7]. In [5], a simple triangular topology conceived for two-user cooperation was combined with beneficial channel codes. As further advances, two-way relay channels (TWRC) and multiple-access relay channels (MARC) were investigated in [6] and [7], respectively, where a turbo-like code was constituted for transmissions over the TWRC and MARC in order to achieve a high diversity gain.

The primary focus of this paper is on finding beneficial relay activation criteria for a simple triangular topology. In sophisticated JCN coded systems, extrinsic information transfer (EXIT) chart analysis may be involved for visualizing the convergence behavior of the iterative detection scheme [8], [9]. Against this background, the novel contribution of this treatise is that an EXIT-chart-aided relay activation scheme is proposed for a low-complexity XOR assisted JCN code.

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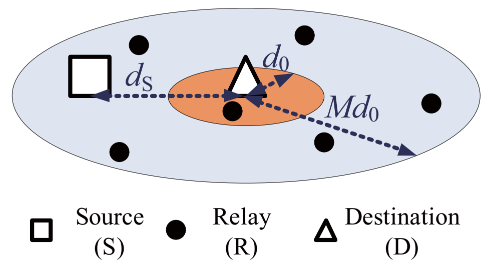


Fig. 1. Network model constituted by source (S), relay (R) and destination (D) nodes.

The rest of this paper is organized as follows. In Sect. II, the problems to be solved in this paper are clarified in the context of the network and signal models considered. Then, the iterative decoding scheme designed for the XOR assisted transmission is analyzed with the aid of EXIT chart in Sect. III. A novel EXIT chart aided relay activation scheme is proposed in Sect. IV. The scheme is characterized with the aid of computer simulations in Sect. V. Finally, the paper is concluded by a brief summary in Sect. VI.

II. System Model and Problem Statements

A. Network model

The network model considered is shown in Fig. 1. For the sake of simplicity, we assume here that there is a single source (S)-and-destination (D) pair separated by the distance $d_{\rm S}$ in the network. The S-D link is assumed to be subject to path loss, shadowing and quasi-static flat fading, where d_0 denotes the distance bound, which guarantees a block error rate (BLER) $\leq \omega$ over all channel realizations. Naturally, we have BLER $> \omega$ when $d_{\rm S} > d_0$. Furthermore, let us assume that $N_{\rm R}$ relay (R) nodes are uniformly distributed within a circular area having a radius of Md_0.

If our objective is simply to improve the achievable BLER for $d_{\rm S} > d_0$, multi-hop transmissions constitute a straightforward solution [10]. However, even though the channel capacity for each link is enhanced owing to the shortened distance, the end-to-end throughput between the S and D nodes is not significantly improved, since the multiple hops require extra radio resources. In other words, multiple copies of the information message have to be relayed. Hence, our goal is to reduce the amount of extra radio resources required by exploiting not only two-hop aided but also XOR assisted transmissions [1].

The D node should send a re-transmission request to an appropriate R node, which can perfectly detect messages from the S node. More specifically, if the cyclic redundancy check (CRC) of the S-D link returns an indicator of successful detection, no relay node is activated and the session is completed by "direct transmissions." Otherwise, assuming that the D node is informed of the list of potential R nodes, which have perfectly decoded the S's message, as well as assuming that the D node is aware of each channel's SNR between the potential R and D nodes with the aid of appropriate control channels, the D node requests re-transmission from an appropriate potential R node by activating "two-hop transmission" or "XOR assisted transmission." The main problem to be solved is to formulate a decision, whether to activate "two-hop transmission" or "XOR assisted transmission" in the potential R nodes distributed in Fig. 1.

B. Signal model

The signal models of the S-D and R-D links are characterized as follows. At the transmitters of the S and R nodes, the information bits to be sent to the D node, namely the variables $c_i(l)$, $i \in \{\mathrm{S}, \mathrm{R}\}$ are mapped to the transmitted symbols $s_i(k)$ each representing one of the Q constellation points $\mathcal{S} \in \{\mathcal{S}_0, \ldots, \mathcal{S}_{Q-1}\}$.

Let the joint impact of path loss, shadowing and quasi-static flat fading be denoted by the coefficient h_i. The received symbol observed at the receiver of the D node is expressed as

$$r_i(k) = h_i s_i(k) + n_i(k), \quad (1)$$

where k represents the discrete time index, $n_i(k)$ is the complex-valued white Gaussian noise process of $\mathcal{CN}(0, N_0)$ and N_0 denotes the one-sided noise power spectral density.

The symbol-to-bit demapper of the D node calculates the extrinsic log likelihood ratio (LLR) $\alpha_i(l)$, which is defined by

$$\alpha_i(l) = \ln \frac{\Pr[r_i(k)|c_i(l) = 1]}{\Pr[r_i(k)|c_i(l) = 0]}. \quad (2)$$

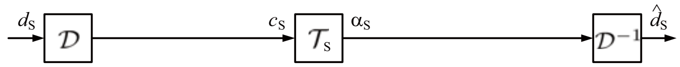
For the ease of analysis, in this paper, we assume the adoption of Gray coded QPSK, having the phases of $\mathcal{S} = \{(-1 - \sqrt{-1})w, (-1 + \sqrt{-1})w, (1 - \sqrt{-1})w, (1 + \sqrt{-1})w\}$ where $w = \sqrt{E_s/2}$ and E_s is the energy of each transmitted symbol. The Gray QPSK mapping allows us to rewrite (2) as

$$\alpha_i(l = 2k - 1) = \frac{2\sqrt{2E_s}}{N_0} \Re\left[h_i^* r_i(k)\right], \quad (3)$$

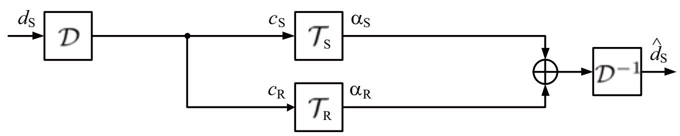
$$\alpha_i(l = 2k) = \frac{2\sqrt{2E_s}}{N_0} \Im\left[h_i^* r_i(k)\right], \quad (4)$$

where $\Re[\cdot]$ and $\Im[\cdot]$ denote real and imaginary parts of complex values, respectively. Substituting (1) into (3) and (4), the extrinsic LLRs $\alpha_i(l)$ may be regarded as the received constellation points of BPSK signalling over Gaussian channels,

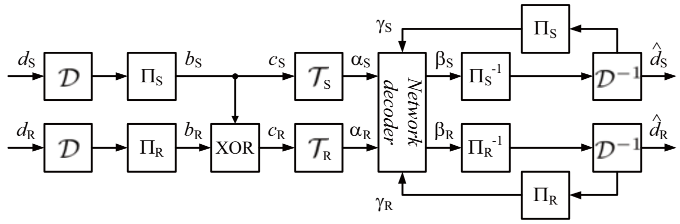
[1]In this contribution, we focus on two-hop transmissions, since the employment of multiple R nodes may reduce effective throughput, as mentioned in [11].



(a) Direct transmissions



(b) Two-hop transmissions



(c) XOR assisted transmissions

Fig. 2. Schematics of the three transceiver modes, where $\mathcal{D}$ and $\mathcal{D}^{-1}$ denote the channel encoder and decoder, respectively. Furthermore, Π_i and Π_i^{-1} are the bit interleaver and deinterleaver, respectively while $\mathcal{T}_i$ indicates the Gaussian LLR signal model $\mathcal{T}(\sigma_i^2)$ defined in (5).

as defined by

$$\alpha_i(l) = \mu_i \tilde{c}_i(l) + \nu_i(l) \triangleq \mathcal{T}(\sigma_i^2), \quad (5)$$

where we have $\tilde{c}_i(l) = 2c_i(l) - 1$ and $\nu_i(l)$ represents the zero-mean real-valued white Gaussian noise process of $\mathcal{N}(0, \sigma_i^2)$. The channel gain μ_i and the variance σ_i^2 are given by $\sigma_i^2 = 4\eta_i$ and $\mu_i = \frac{\sigma_i^2}{2}$, where η_i denotes the instantaneous received SNR, which is defined by $\eta_i = |h_i|^2 \frac{E_s}{N_0}$.

Since the ratio of the channel gain μ_i and of the variance σ_i^2 obeys $\mu_i = \sigma_i^2/2$, the consistency condition of the probability density function for $\alpha_i(l)$ is satisfied [12]. Therefore, the mutual information (MI) of (5), which is equivalent to the channel capacity constrained by BPSK signaling, may be closely-approximated by

$$I_i = J(\sigma_i) = J(2\sqrt{\eta_i}) \approx \left(1 - 2^{-H_1 \sigma_i^{2H_2}}\right)^{H_3}, \quad (6)$$

where the mapping-specific parameters are $H_1 = 0.3073$, $H_2 = 0.8935$, and $H_3 = 1.1064$, which are obtained by least-squared curve fitting [13]. Furthermore, the inverse function of (6) is given by

$$\sigma_i = J^{-1}(I_i) \approx \left(-\frac{1}{H_1} \log_2(1 - I_i^{\frac{1}{H_3}})\right)^{\frac{1}{2H_2}}. \quad (7)$$

C. Transciever schematic for each transmission mode

The transceiver schematics designed for the three transmission modes considered are depicted in Fig. 2.

1) Direct transmissions: As shown in Fig. 2(a), the information bits $d_{\mathrm{S}}(m)$ to be sent to the D node from the S node transmitter, are encoded by a channel encoder in order to form the coded bits $c_{\mathrm{S}}(l)$. The coded bits $c_{\mathrm{S}}(l)$ are mapped to the transmitted symbols, sent over the wireless channel and demapped to generate the extrinsic LLRs $\alpha_{\mathrm{S}}(l)$. The extrinsic LLRs $\alpha_{\rm S}(l)$ are delivered to the channel decoder (CD), which outputs the estimated information bits $\hat{d}_{\rm S}(m)$ after error correction decoding.

2) Two-hop transmissions: Recall that the appropriately selected R node has perfect knowledge of the information message $d_{\rm S}(m)$, as shown in Fig. 2(b). Once the D node's CRC detects an error, a copy of the message is relayed via the R node to the D node. At the receiver, the extrinsic LLRs $\alpha_{\rm S}(l)$ provided by the S node assist us in detecting the information message $d_{\rm S}(m)$ of Fig. 2(b). Since the LLRs $\alpha_{\rm S}(l)$ and $\alpha_{\rm R}(l)$ are conveyed over independent channels during the first broadcast and the second cooperative phases, respectively, the extrinsic LLRs of the joint probability are given by

$$\ln \frac{\Pr[r_{\rm S}(k), r_{\rm R}(k)|c_i(l)=1]}{\Pr[r_{\rm R}(k), r_{\rm R}(k)|c_i(l)=0]} = \ln \prod_i \frac{\Pr[r_i(k)|c_i(l)=1]}{\Pr[r_i(k)|c_i(l)=0]} = \alpha_{\rm S}(l) + \alpha_{\rm R}(l). \quad (8)$$

Instead of simply using $\alpha_{\rm S}(l)$ as in conventional direct transmission, the combined LLRs are delivered to the CD, in order to derive more reliable estimates of the information bits $\hat{d}_{\rm S}(m)$.

3) XOR assisted transmissions: Since the selected R node has its own message for transmission to the D node in this mode, each information message $d_i(m)$ is independently encoded and interleaved, in order to generate the coded bits $b_i(l)$. Then, the XORed bits of $c_{\rm R}(l) = b_{\rm S}(l) \oplus b_{\rm R}(l)$ are generated, where the null element in GF(2) is assumed to be zero. The XORed bits $c_{\rm R}(l)$ are then mapped to the QPSK symbols, transmitted over the wireless channels, and then the extrinsic LLRs $\alpha_{\rm R}(l)$ are generated.

If we focus our attention purely on $\alpha_{\rm R}(l)$, we encounter the following ambiguity problem. For example, it is impossible to judge, whether $b_{\rm S} = b_{\rm R} = 1$ or $b_{\rm S} = b_{\rm R} = 0$ is correct, when we have $c_{\rm R} = 0$, since the XORed value of $c_{\rm R}$ becomes zero for both cases. In order to resolve this ambiguity problem, the pre-calculated extrinsic LLR $\alpha_{\rm S}(l)$ assists in detecting the information message $d_{\rm S}(m)$ and $d_{\rm R}(m)$ with the aid of the iterative detection process of Fig. 2(c), where different random interleavers are employed, in order to improve the attainable performance.

Maximum *a-posteriori* probability (MAP) detection is applied in order to decompose the XORed bits of $c_{\rm S}(l)$ and $c_{\rm R}(l)$ into the corresponding pair of coded bits $b_{\rm S}(l)$ and $b_{\rm R}(l)$. We refer to this process as the "Network decoder (ND)." The ND provides the extrinsic LLRs $\beta_i(l)$ for the coded bits $b_i(l)$. After de-interleaving the LLRs $\beta_i(l)$, they are delivered to the CDs of Fig. 2(c), in order to calculate the *a-priori* LLRs $\gamma_i(l)$, which are forwarded to the ND via the interleavers $\Pi_{\rm S}$ and $\Pi_{\rm R}$ as *a-priori* probabilities. The exchange of the LLRs $\beta_i(l)$ and $\gamma_i(l)$ between the ND and CDs is capable of resolving the above-mentioned ambiguity problem. After several iterations, the estimated information bits $\hat{d}_{\rm S}(m)$ and $\hat{d}_{\rm R}(m)$ are obtained by the CDs.

A specific problem to be considered here is that the ND process cannot always resolve the XORed bits, since their separability depends on the SNRs experienced in both the S-D and R-D links. Hence, this relationship is investigated in the next section.

III. Iterative Detection of XOR Assisted Relaying

Without loss of generality, the indices m, l and k are omitted for ease of notational simplicity.

A. Iterative decoding of the JCN codes

After observing $\alpha_{\rm S}$ and $\alpha_{\rm R}$, the extrinsic LLRs β_i are derived by the ND, expressed as

$$\beta_i = \ln \frac{\Pr[b_i = 1|\alpha_{\rm S}, \alpha_{\rm R}]}{\Pr[b_i = 0|\alpha_{\rm S}, \alpha_{\rm R}]} - \gamma_i, \quad (9)$$

where γ_i is an *a-priori* LLR fed back from each CD to the ND, as defined by $\gamma_i = \ln \frac{\Pr[b_i=1]}{\Pr[b_i=0]}$. Note that γ_i is zero at the first iteration, because no *a-priori* knowledge is available about b_i at this stage. In order to derive the *a-posteriori* probability $\Pr[b_i|\alpha_{\rm S}, \alpha_{\rm R}]$ in (9), the marginalization of the joint probability and Bayes' theorem play a key role, yielding

$$\Pr[b_i|\alpha_{\rm S}, \alpha_{\rm R}] = \sum_{b_j} \Pr[b_{\rm S}, b_{\rm R}|\alpha_{\rm S}, \alpha_{\rm R}] \propto \sum_{b_j} \Pr[\alpha_{\rm S}, \alpha_{\rm R}|b_{\rm S}, b_{\rm R}] \Pr[b_{\rm S}, b_{\rm R}], \quad (10)$$

where we have $j \neq i$ $(i, j \in \{{\rm S}, {\rm R}\})$. Since the S-D and R-D links experience independent fading during the two different transmission phases, the joint probability may be decomposed to

$$\Pr[\alpha_{\rm S}, \alpha_{\rm R}|b_{\rm S}, b_{\rm R}] = \Pr[\alpha_{\rm S}|b_{\rm S}, b_{\rm R}] \Pr[\alpha_{\rm R}|b_{\rm S}, b_{\rm R}] = \Pr[\alpha_{\rm S}|c_{\rm S}] \Pr[\alpha_{\rm R}|c_{\rm R} = b_{\rm S} \oplus b_{\rm R}]. \quad (11)$$

Furthermore, since the bits $b_{\rm S}$ and $b_{\rm R}$ are generated from independent random sources, we have $\Pr[b_{\rm S}, b_{\rm R}] = \Pr[b_{\rm S}] \Pr[b_{\rm R}]$.

Let $\mathcal{C}_i$ and $\mathcal{B}_i$ be the ratios of the LLR α_i and of the coded bit b_i defined by

$$\mathcal{C}_i = \frac{\Pr[\alpha_i|c_i = 1]}{\Pr[\alpha_i|c_i = 0]}, \quad \mathcal{B}_i = \frac{\Pr[b_i = 1]}{\Pr[b_i = 0]}. \quad (12)$$

After some simple algebraic manipulations, (9) is rewritten as

$$\beta_{\rm S} = \ln \mathcal{C}_{\rm S} + \ln \frac{\mathcal{C}_{\rm R} + \mathcal{B}_{\rm R}}{1 + \mathcal{C}_{\rm R}\mathcal{B}_{\rm R}}, \quad (13)$$

$$\beta_{\rm R} = \ln \frac{\mathcal{C}_{\rm R} + \mathcal{C}_{\rm S}\mathcal{B}_{\rm S}}{1 + \mathcal{C}_{\rm R}\mathcal{C}_{\rm S}\mathcal{B}_{\rm S}}. \quad (14)$$

By exploiting that the extrinsic LLRs α_i may be regarded as being Gaussian distributed in conjunction with BPSK signaling, as mentioned in Sect. II.B, the ratios $\mathcal{C}_i$ are reduced to

$$\mathcal{C}_i = \frac{\exp\left[-\left(\alpha_i - \frac{\sigma_i^2}{2}\right)^2 / (2\sigma_i^2)\right]}{\exp\left[-\left(\alpha_i + \frac{\sigma_i^2}{2}\right)^2 / (2\sigma_i^2)\right]} = \exp\left[\alpha_i\right]. \quad (15)$$

Furthermore, since we have $\mathcal{B}_i = \exp(\gamma_i)$, (13) and (14) may be rewritten as

$$\beta_{\rm S} = \alpha_{\rm S} + (\alpha_{\rm R} \boxplus \gamma_{\rm R}), \quad (16)$$

$$\beta_{\rm R} = \alpha_{\rm R} \boxplus (\alpha_{\rm S} + \gamma_{\rm S}), \quad (17)$$

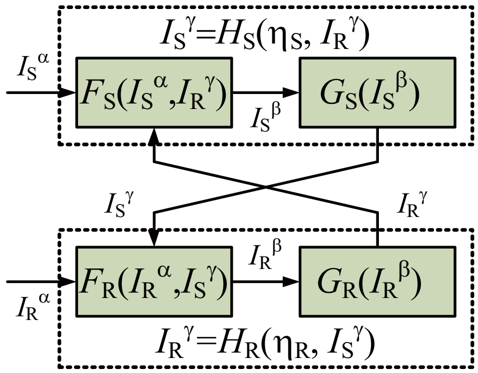


Fig. 3. EXIT model of XOR assisted transmission.

where ⊞ denotes the boxplus operator defined by Hagenauer et al. [14] as [2]

$$A \boxplus B = \ln \frac{\exp(A) + \exp(B)}{1 + \exp(A + B)}. \tag{18}$$

B. EXIT chart analysis

Figure 3 shows on EXIT chart analysis model. Based on (6) representing the variance of the LLR-to-MI conversion, the LLRs α_i, β_i and γ_i are transformed to the corresponding MI, which are denoted by I_i^α, I_i^β and I_i^γ, respectively. Then, the EXIT functions, which are defined as the input/output relationships, for ND F_i and for the CD G_i are denoted by

$$I_i^\beta = F_i\left(I_i^\alpha, I_j^\gamma\right), \tag{19}$$

$$I_i^\gamma = G_i\left(I_i^\beta\right), \tag{20}$$

where we have $i \neq j$.

Recall that the function F_i is constituted by the sum and boxplus operations, when genarating the extrinsic LLRs. According to [9], the MI after the sum and boxplus operations between the extrinsic LLRs A and B are derived by

$$A + B \rightarrow J\left(\sqrt{[J^{-1}(I_A)]^2 + [J^{-1}(I_B)]^2}\right), \tag{21}$$

$$A \boxplus B \rightarrow 1 - J\left(\sqrt{[J^{-1}(1 - I_A)]^2 + [J^{-1}(1 - I_B)]^2}\right), \tag{22}$$

where I_A and I_B represent the MI for the LLRs A and B, respectively [3]. Substituting these MI calculations into (16) and (17), I_S^β and I_R^β are expressed in (23) and (24).

On the other hand, the EXIT functions of the CD are uniquely determined by the channel code to be used. When a recursive systematic convolutional (RSC) encoder having the octal generator polynomials of $[1, 15/13]_{\rm oct}$ is employed for both the S and R nodes, the EXIT function may be approximated by

$$I_i^\gamma = G_i(I_i^\beta) \approx \left(1 - 2^{-D_1 (I_i^\beta)^{D_2}}\right)^{D_3}, \tag{25}$$

where the mapping-specific parameters are $D_1 = 17.7954$, $D_2 = 3.4600$, and $D_3 = 1.7490$, which were calculated by least-squared curve fitting under the assumption of having sufficiently high code length.

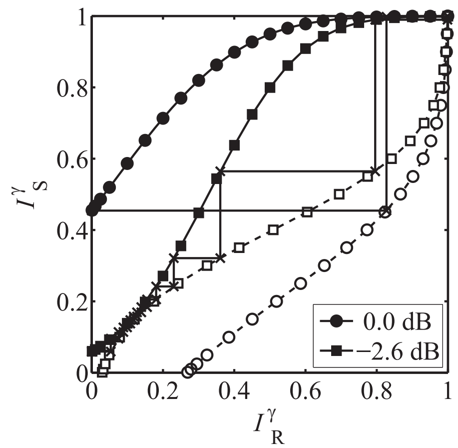


Fig. 4. EXIT chart for the XOR assisted transmission at SNR $\eta_R = 5.0$ dB. The dB values in the legend denotes instantaneous received SNR of the S-D link η_S. Solid and dashed curves with black and white marker faces represent H_S and H_R, respectively. Stair lines denote EXIT trajectories.

Substituting (19) into (20), it is clear that I_i^γ is uniquely determined by I_i^α and I_j^γ, which is expressed as

$$I_i^\gamma = G_i\left[F_i\left(I_i^\alpha, I_j^\gamma\right)\right] \triangleq H_i\left(\eta_i, I_j^\gamma\right). \tag{26}$$

The transfer function H_i indicates the fact that the decoder's iterative behavior may be readily characterized by observing the MI exchanges of I_S^γ and I_R^γ for a given combination of SNRs η_S and η_R without any consideration of I_i^β.

The resultant EXIT chart is depicted in Fig. 4. The instantaneous received SNR of the R-D link is fixed to η_R = 5.0 dB, while that of the S-D link to η_S = 0.0 and -2.6 dB. Figure 4 implies that the EXIT trajectories cannot reach the (1,1) point for any combinations of η_S <-2.6 dB and η_R=5.0 dB, since the EXIT curves intersect each other, hence the system results in detection errors. In other words, the R node is capable of operating without block detection error events, when $\eta_S \geq$-2.6 dB and η_R=5.0 dB. However, we have to mention that there is a mismatch between decoder's convergence threshold estimated from the EXIT chart and that found by BLER simulations. This is because a sufficiently long channel code and an infinite number of iterations are assumed in the EXIT analysis, whereas an insufficiently long channel code and a finite number of iterations are assumed in the BLER simulations.

IV. EXIT Chart Aided Relay Activation

The problem of finding an appropriate R node is equivalent to finding a node in the network, which satisfies the SNR requirement η_R under a given condition of η_S. The most straight-forward way of finding the appropriate R node is to draw the EXIT trajectories for all potential R nodes. If the trajectory reaches the $I_S^\gamma = I_R^\gamma \approx 1.0$ point, the node is capable of supporting XOR assisted transmission. However, this procedure is imperfect, since there is a mismatch between the SNR requirement estimated by EXIT chart analysis and

[2] In [14], the null element in GF(2) is +1, while it was set to zero in this paper. Therefore, the definition of the boxplus operater has the opposite sign in comparison to [14].

[3] Equation (22) was originally developed for binary erasure channels, but it remains fairly accurate also for AWGN channels.

$$I_{\rm S}^{\beta} = J\left(\sqrt{[J^{-1}(I_{\rm S}^{\alpha})]^2 + \left[J^{-1}\left(1 - J\left(\sqrt{[J^{-1}(1-I_{\rm R}^{\alpha})]^2 + [J^{-1}(1-I_{\rm R}^{\gamma})]^2}\right)\right)\right]^2}\right), \quad (23)$$

$$I_{\rm R}^{\beta} = 1 - J\left(\sqrt{[J^{-1}(1-I_{\rm R}^{\alpha})]^2 + [J^{-1}\left(1 - J\left([J^{-1}(I_{\rm S}^{\alpha})]^2 + [J^{-1}(I_{\rm S}^{\gamma})]^2\right)\right)]^2}\right). \quad (24)$$

BLER simulations. Nevertheless, it is possible to set a safety-margin in the EXIT chart based activation criterion. However, the probability of block error events caused by the mismatch is low. Therefore, the introduction of safety-margin may not be necessary.

With the objective of improving the achievable throughput of the network, we propose simple criteria for the relay activation in this section. When the CRC indicates that the direct transmission failed, the procedure refers to the list of potential R nodes and selects the transmission mode by obeying the following two criteria.

A. Criterion for XOR assisted transmissions

The following process is activated for each potential R node having own messages to be sent to the D node. If there are no such R nodes, we proceed to the next criterion for the two-hop transmission mode.

1) Initialize: $I_{\rm S}^{\gamma} = I_{\rm R}^{\gamma}$=0.0.
2) Update $I_{\rm S}^{\gamma}$ and $I_{\rm R}^{\gamma}$ as many times as the affordable number of iterations with the aid of the following expressions:
$$I_{\rm S}^{\gamma} = H_{\rm S}\left(\eta_{\rm S}, I_{\rm R}^{\gamma}\right), \quad I_{\rm R}^{\gamma} = H_{\rm R}\left(\eta_{\rm R}, I_{\rm S}^{\gamma}\right).$$
3) Check whether both $I_{\rm S}^{\gamma}$ and $I_{\rm R}^{\gamma}$ are higher than or equal to a threshold value $I_{\rm th}$:
$$(I_{\rm S}^{\gamma} \geq I_{\rm th}) \quad \text{AND} \quad (I_{\rm R}^{\gamma} \geq I_{\rm th}),$$
where $I_{\rm th}$ is a system parameter introduced for controlling the BLER. Among the potential R nodes, which satisfy the above conditions, the specific node having the highest SNR $\eta_{\rm R}$ is activated for XOR assisted transmissions. If there are no such nodes, go to the next.

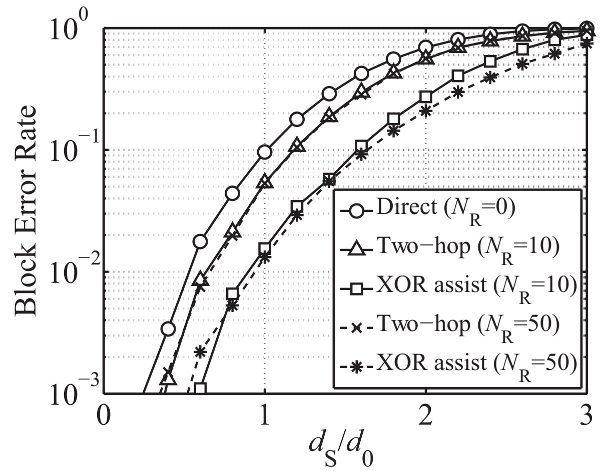
B. Criterion for two-hop transmissions

The following process is evaluated for each potential R node. If there are no such nodes, the transmissions are terminated.

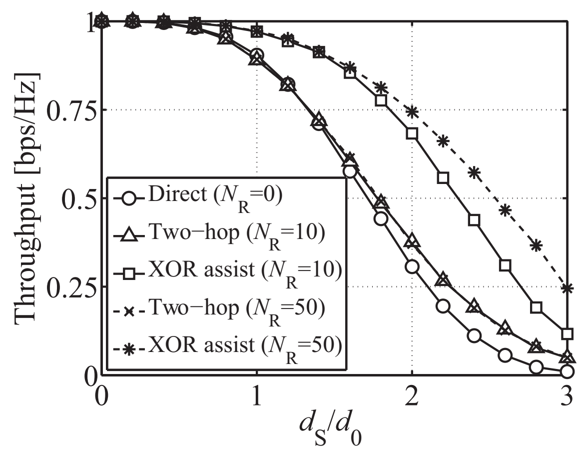
1) Check wheter $(\eta_{\rm S} + \eta_{\rm R})$ is higher than or equal to a threshold value $\eta_{\rm th}$:
$$(\eta_{\rm S} + \eta_{\rm R}) \geq \eta_{\rm th},$$
where $\eta_{\rm th}$ is also a system parameter used for controlling BLER. Among the potential R nodes, which satisfy the above condition, the specific node having the highest SNR $\eta_{\rm R}$ is activated for the two-hop transmissions.

V. Numerical Results

In order to characterize the proposed relay activation scheme, computer simulations have been conducted. In the network model of Fig. 1, we assumed having $N_{\rm R}$ = 0, 10, or 50. Note that $N_{\rm R}$=0 is equivalent to the direct transmissions. The R nodes were uniformly distributed in a circular area having a radius of $3d_0$ (M=3). The distance d_0 was set to a value, which satisfies BLER $\leq \omega = 0.1$. For simplicity, each R node was assumed to always have messages ready to be sent to the D node in its buffer.



(a) Block error rate.



(b) Troughput.

Fig. 5. Performance of the EXIT chart aided relay activation. The dashed and solid curves show the attainable performances in the case of $N_{\rm R}$ =10 and 50, respectively.

The path-loss exponent in the wireless network was assumed to be 3.5. Furthermore, log-normal shadowing with a standard deviation of 8 dB and flat Rayleigh fading having complex-valued channel coefficients obeying $\mathcal{CN}(0, 1)$ were assumed. Gray coded QPSK was used for each link. In the channel encoders of both links, half-rate RSC schemes having a code memory of three and the octal generator polynomials of $[1, 15/13]_{\mathrm{oct}}$ were used. Each RSC encoder processed 1024 information bits in order to form 2048 coded bits per transmission block. The coded blocks were decoded by the Max-Log-Map decoder with the Jacobian logarithm. Then, the maximum number of iterations was set to 16. The threshold values of I_{th} and η_{th} were set to 0.999 and 5.21 dB, respectively[4]. Information of the instantaneous received SNRs η_{S} and η_{R} were assumed to be perfectly known at the D node.

The achievable BLER and throughput for information blocks d_{S} are characterized in Figs. 5(a) and 5(b), respectively. The curves plotted for "Two-hop" represent transmissions without the criterion A for XOR assisted transmissions. In other words, the D node evaluates only criterion B for deciding the activation of two-hop transmissions. The dashed and solid curves represent the performances for the case of N_{R} =10 and 50, respectively. The throughput T is defined by

$$T = \frac{(1 - BLER)N_{\mathrm{d}}}{N_{\mathrm{s}}N_{\mathrm{phase}}} \quad [\mathrm{bps/Hz}], \tag{27}$$

where N_{d} and N_{s} represent the numbers of information data bits and symbols embedded in one block, respectively. N_{phase} is the number of phases to be occupied for each transmission mode. Explicitly, when two-hop transmission is selected, we have $N_{\mathrm{phase}} = 2$, otherwise $N_{\mathrm{phase}} = 1$.

The horizontal axis d_s/d_0 denotes the distance between S and D nodes normalized by d_0. In this case, the average received SNR at the arbitrary distance d_i is expressed as

$$\Gamma(d_i) = \Gamma(d_0)\left(\frac{d_i}{d_0}\right)^{-3.5} \quad (i \in \{\mathrm{S}, \mathrm{R}\}), \tag{28}$$

where d_{R} is the distance between R and D nodes, while $\Gamma(d_0)$ is the SNR required to satisfy BLER=0.1 under the given shadowing and fading conditions. In the present simulation conditions, $\Gamma(d_0)$ is 25.4 dB [5].

Let us now focus our attention on Fig. 5(a). Compared to direct transmissions, two-hop transmissions using N_{R}=10 and 50 guarantees 20% extension of the cell-radius, while achieving BLER=10^{-1}. From a different perspective, the extension implies that a 2.7 dB $[10\log_{10}(1.0/1.2)^{-3.5}]$ power gain can be obtained, when the distance d_{S} is the same for both direct and two-hop transmissions. On the other hand, XOR-assisted transmissions for N_{R} =10 and 50 guarantee an approximately 60% extension of the coverage distance, while achieving BLER=10^{-1}. The extension implies that a 7.1 dB $[10\log_{10}(1.0/1.6)^{-3.5}]$ power gain can be obtained. Therefore, the EXIT chart aided relay activation is also effective in terms of reducing the required transmit power.

Next, let us focus our discussions on Fig. 5(b). Two-hop transmissions cannot guarantee an increased throughput, since the extra copies of the messages occupy extra wireless resources. On the other hand, XOR-assisted transmissions significantly improve the attainable throughput. More specifically, at d_{S}/d_0 = 1.6 which is the maximum distance, where we are able to maintain BLER=10^{-1} for the XOR assisted transmission, we can confirm a 55% increase of the throughput compared to classic direct transmissions. Therefore, it is clear that XOR-assisted transmissions are capable of simultaneously improving both the BLER (i.e. outage) and the throughput. Furthermore, we can confirm the tendency that the throughput is enhanced more substantially for long distances d_{S}, when there is a larger number of relay candidates N_{R}.

[4]The value of η_{th}=5.21 dB achieves BLER=10^{-2} in AWGN channels.

[5]In order to reduce $\Gamma(d_0)$, space-, frequency- and time-diversity may be used. For the sake of simplicity, the diversity order was fixed to one.

VI. Conclusion

In this paper, an EXIT chart aided relay activation scheme was proposed for JCN coded systems. The main problem to be solved was to formulate the decision criteria, whether to activate "two-hop transmission" or "XOR assisted transmission" in the R nodes of the network. In order to address the problem, the criteria were related to the predicted EXIT trajectories of all potential R nodes. We demonstrated that the EXIT chart aided relay activation scheme is effective in terms of improving both the outage probability of the communication link, as well as the throughput of the network.

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