Joint Adaptive Network-Channel Coding for Energy-Efficient Multiple Access Relaying

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***Abstract*—An energy-efficient orthogonal multiple access relay channel (MARC) system is developed where accumulator and differential detection (DD) are used at the source and relay nodes, respectively. However, the weak decoding capability of DD degrades the frame error fare (FER) performance of the orthogonal MARC system if the conventional decoded-and-forward relaying strategy is applied. In this paper, a novel joint adaptive network-channel coding (JANCC) technique is proposed to support DD by making efficient use of the erroneous estimates output from DD. In the JANCC technique, the destination constructs a vector identifying the indexes of the source nodes whose information parts contain errors, and sends it to the relay to request a retransmission. The relay performs network coding by taking the exclusive-OR (XOR)-operation only over the stored estimates specified by the identifier vector, which aims to avoid unnecessary erroneous estimates being coded. In addition, a bit-flipping probability p_{nc} is obtained between the two sequences, one is the network-coded sequence sent from the relay, and the other is their corresponding XOR-ed information sequence. The decoding algorithm of JANCC exploits the probability p_{nc} at the destination to update the Log-Likelihood Ratio during the iterative decoding process. Hence, the information sequences received at the destination are able to be recovered even though the redundancy forwarded from the relay is generated from the erroneous estimates. Compared with the system where the iterative decoding is performed at the relay, the utilization of DD significantly reduces the computational complexity, which leads to meaningful power saving with only a small loss in the FER performance.**

***Index Terms*—Multiple Access Relay Channel, different detection, automatic repeat request, joint channel-network coding.**

I. Introduction

COOPERATIVE wireless networks have attracted a lot of attention of the wireless communication research community recently, since they provide a lot of design flexibility in the form of, e.g., diversity-multiplexing tradeoff (DMT), coverage extension, and multiple users' Quality-of-Service (QoS) management. One of the cooperative network structures is Multiple Access Relay [1], which consists of N source nodes, one relay and one common destination; the role of the relay is to assist the source nodes to improve the probability of successful transmission to the destination. Many excellent joint network-and-channel coding (JNCC) techniques for orthogonal multiple access relay channel (MARC) with $N = 2$ can be found in the literature [2]–[7]. However, only a few publications consider orthogonal MARC systems with an arbitrary number of source nodes in their designs. In many cases the designs for orthogonal MARC systems with N greater than two require higher complexity in structure.

In addition, the powerful codes, such as turbo codes [8] or low density parity check (LDPC) codes [9], are applied at the relay in the most of the techniques for network designs [2]–[5], [10]. Although the application of powerful codes guarantees the high probability of successful decoding at the relay, the application causes heavy computation load; furthermore, as the number of source nodes increases, due to the heavy computation for the signal processing of each source node, power consumption is also expected to increase, which reduces the battery longevity of the relay.

In the conventional decoded-and-forward (DF)-based orthogonal MARC network designs [11], [12], the relay only forwards the successfully decoded information data transmitted from the source nodes, and discards the sequence estimates containing errors to avoid the error propagation in the JNCC decoding process. However, discarding the erroneous sequence estimates obtained at the relay degrades the transmission efficiency, because the estimates still contain a lot of useful information, which are helpful for reconstructing the transmitted signals from the source nodes at the destination. Hence, several emerging design schemes have been proposed [13]–[15] for preserving the information of the erroneous estimates at the relay, and forward the estimates in an analog form or their quantized versions. However, even with proper quantization techniques, relaying the signals requires more bandwidth for the representation of the *soft bits*.

Motivated by the disadvantageous properties of the previous works, an energy-efficient and low-complexity orthogonal MARC system combined with automatic repeat request (ARQ) [16] was developed in our previous work [17], where an accumulator (ACC) [18], equivalent to a differential encoder, is used at each source node after a recursive systematic convolutional (RSC) encoder. The use of the ACC is to ensure that the extrinsic information transfer (EXIT) convergence tunnel open until a point very close to the (1.0, 1.0) mutual information point [19]. In the broadcast (BC) phase, a very simple differential detection (DD) is performed at the relay

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and the information part is only *extracted* [20] from the output of the differential detector; the iterative decoding between the decoders of the RSC code and ACC is *not* performed.

However in [17], only two source nodes were assumed in the system model. In addition, although we have observed the bit-flipping probability p_{nc} between the network-coded sequence sent from the relay and their corresponding XOR-ed information sequence, the aid of higher layer protocol setting is still needed for the destination to acquire the knowledge of the probability p_{nc}, which is less practical. Furthermore, all the information estimates output from the DD were network coded at the relay, where unnecessary erroneous estimates may be coded, which increases the bit-flipping probability p_{nc}, and thus, the correction capability of the decoder at the destination is degraded.

This paper aims to further improve our previous work in [17]. The system model in [17] is first generalized with an arbitrary number of source nodes. We then propose a novel joint adaptive network-channel coding (JANCC) technique, where after completing the decoding of all the information sequences transmitted from the source nodes, the destination constructs a vector identifying the indexes of the source nodes whose information parts contain errors. The identifier vector is then sent to the relay to request a retransmission of the information sequences decoded in error at the destination, and the relay performs network coding by taking the XOR-operation *only* over its received estimates of the information sequences specified by the identifier vector. The decoding of JANCC is performed at the destination, where the bit-flipping probability p_{nc} is *estimated* by using the proposed algorithm and effectively utilized in the decoding process. Finally, the reduction in terms of the computational complexity is analyzed.

The main contributions of the paper are summarized as follows.

- By making the efficient use of the erroneous estimates of the information sequences received at the relay and by forwarding the coded version of them to the destination as additional redundancy, it is possible to correctly recover the information estimates transmitted via the source-destination (SD) links, which improves the frame error rate (FER) performance over the conventional DF relay strategies for MAC relaying systems.
- Lower bit-flipping probability p_{nc} can be obtained with adaptively performing network coding on the estimates extracted from the DD, which enhances the decoding capability of the JNCC and thus FER performance can be improved.
- The computational complexity of the relay is significantly reduced by replacing the iterative decoding of an iteratively-decodable powerful codes by simply extracting the information (systematic) part output from DD. This advantageous characteristic is more meaningful, when the number of source nodes increases.
- The energy consumption for the channel estimation can be eliminated at the relay by utilizing DD because it does not need channel estimation. This advantageous characteristic is, again, more meaningful, when the number of source nodes increases.

The rest of this paper is organized as follows. Section II introduces the developed orthogonal MARC system model. A detailed description of the proposed JANCC and its corresponding decoding techniques are presented in Section III. Section IV presents simulation results to demonstrate the performance of the developed system combined with the proposed JANCC techniques, in terms of average FER and the computational complexity. The average throughput evaluation results are also provided in Section IV. Finally, Section V concludes this paper with some concluding remarks.

II. System model

Fig. 1 depicts a block diagram of the developed orthogonal MARC system assumed in this paper, where there are N source nodes, one common relay node R, and one common destination node D. Each node is equipped with a single antenna, and R is assumed to be connected with D via a half-duplex link. As shown in Fig. 1, each source node S_i, $i = 1, 2, ..., N$, generates its binary and cyclic redundancy check (CRC) [21] encoded information sequence $\mathbf{u}_i = \{u_i(k)\}_{k=1}^{K}$. All the information sequences are assumed to be statistically independent.

Each sequence $\mathbf{u}_i$ is interleaved and encoded by an serially concatenated convolutional code (SCCC) where the SCCC is composed of a rate-K/M RSC encoder C_S and rate-1 ACC. The corresponding coded bit sequence $\mathbf{x}_i = \{x_i(m)\}_{m=1}^{M}$ is modulated by binary phase-shift keying (BPSK) and broadcasted to R and D at the each source node's dedicated independent time slot.

Without loss of generality, all transmitted signals have unit power. All the links are assumed to suffer from block Rayleigh fading, and thus the signal vectors received at R and D are

$$\mathbf{y}_{iR} = h_{iR} \cdot \mathbf{x}_i + \mathbf{n}_{iR}$$
$$\mathbf{y}_{iD} = h_{iD} \cdot \mathbf{x}_i + \mathbf{n}_{iD} \quad (1)$$

with $i = 1, 2, ..., N$, where h_{iR} and h_{iD} indicate the channel coefficients of SR and SD links with the source node S_i. $\mathbf{n}_{iR}$ and $\mathbf{n}_{iD}$ indicate the vectors of independent zero-mean complex additive white Gaussian noise (AWGN) at R and D with the source node S_i, respectively, with variance $\sigma_{iR}^2 = \sigma_{iD}^2 = \sigma^2$ per dimension. Block Rayleigh fading is assumed, with which h_{iR} and h_{iD} are assumed to be constant over one coded sequence but vary independently transmission-by-transmission and link-by-link.

If D identifies that all users' information sequences are successfully decoded by the CRC error detection, acknowledgement (ACK) is sent back to the source nodes, and the source nodes broadcast their following information sequences at their dedicated time slots. Otherwise D sends to R a redundancy retransmission request via the feedback channel[1], and once receiving the retransmission request, R transmits

[1]The feedback channel is assumed to be error-free. This assumption is reasonable because the retransmission request can be represented by N bits, as detailed in Section III, which is protected by using a powerful channel coding.

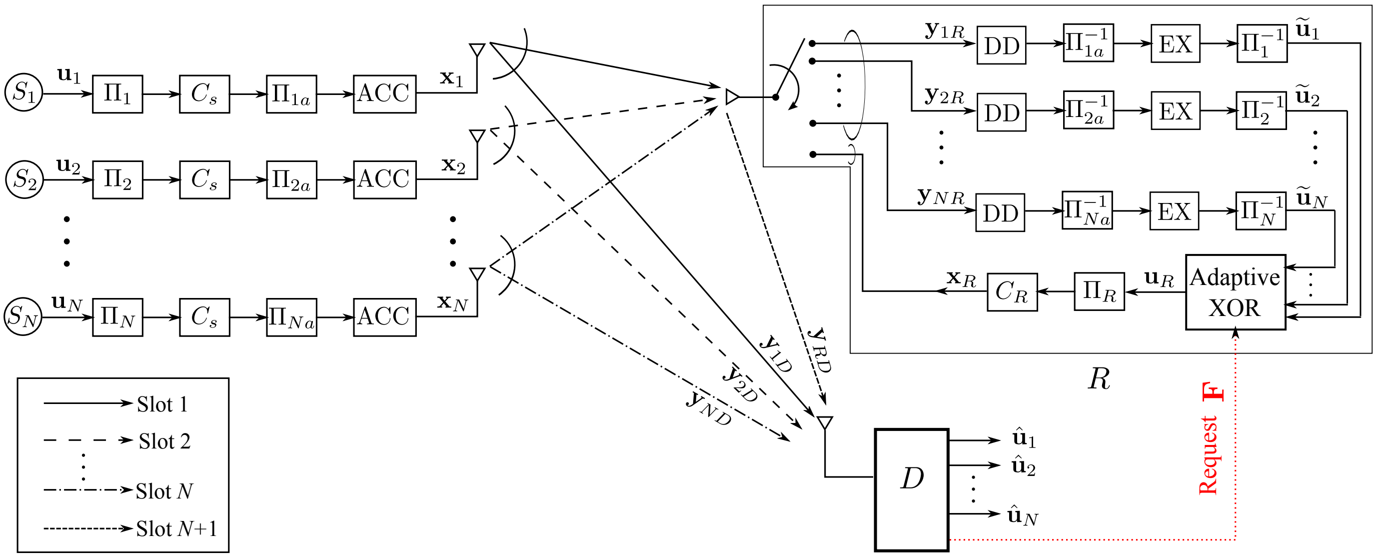

Fig. 1. Orthogonal Multiple Access Relay Channel model with N source nodes combined with ARQ. EX represents to extract the systematic part of the sequence output from DD.

BPSK-modulated coded sequence $\mathbf{x}_R$ to D via the relay-destination (RD) link, as

$$\mathbf{y}_{RD} = h_{RD} \cdot \mathbf{x}_R + \mathbf{n}_{RD} \tag{2}$$

where h_{RD} and $\mathbf{n}_{RD}$ indicate the channel coefficient and AWGN vector of the RD link with variance $\sigma_{RD}^2 = \sigma^2$, respectively. In this paper, it is assume that $E[|h_{iR}|^2] = E[|h_{iD}|^2] = E[|h_{RD}|^2] = 1$, with $i = 1, 2, ..., N$. The instantaneous signal-to-noise power ratios (SNR) γ_{iR}, γ_{iD} and γ_{RD} of the links are then given by

$$\begin{aligned}\gamma_{iR} &= |h_{iR}|^2 \cdot \Gamma_{iR} \\ \gamma_{iD} &= |h_{iD}|^2 \cdot \Gamma_{iD} \\ \gamma_{RD} &= |h_{RD}|^2 \cdot \Gamma_{RD}\end{aligned} \tag{3}$$

where Γ_{iR} and Γ_{iD} represent the average SNRs of the SR and SD links connected to the source node S_i, respectively. Γ_{RD} is the average SNR of the RD link. Neither large scale path-loss gain nor shadowing is included in (1) and (2), and the processing delay at R is not considered, for simplicity.

Instead of performing the iterative decoding of the SCCC, the relay R utilizes very simple DD for detecting the received signal vector $\mathbf{y}_{iR}$ transmitted from the source node S_i. The aim of utilizing DD is to reduce the power consumption by eliminating the necessity of channel estimation; furthermore, R only extracts the systematic part of the sequence output from DD to obtain the estimates of information sequences $\tilde{\mathbf{u}}_i = \{\tilde{u}_i(k)\}_{k=1}^K$, which further reduces the complexity for obtaining $\tilde{\mathbf{u}}_i$ at R. For notation simplicity, the detection strategy mentioned above for obtaining the sequences $\tilde{\mathbf{u}}_i$ at R is referred to as DDEX in this paper.

With the process for estimating the information sequences at R, it is highly probable that the sequences $\tilde{\mathbf{u}}_i$ obtained at R contain errors by using DDEX because the decoding of C_S is not performed. The average FER performance of the SR link with using DDEX and with performing the iterative decoding of the SCCC were evaluated by [22], respectively. It is found that when R performs the iterative decoding of the SCCC, the FER performance of the SR link is very close to the outage probability, however, it is about 12 dB away from the outage with using the DDEX strategy although the decoding complexity of the SCCC is eliminated.

III. Proposed Techniques

The drawback of the DDEX detection strategy is that the estimates of the information sequences $\tilde{\mathbf{u}}_i$ obtained at R contain errors with a high probability. Therefore, a joint adaptive network-channel coding (JANCC) and its corresponding decoding techniques are proposed in this section, where the erroneous estimates obtained at R after the DDEX strategy are further utilized to help recover the information sequences decoded in error at D.

A. *Joint adaptive network-channel coding (JANCC)*

The received signal vector $\mathbf{y}_{iD} = \{y_{iD}(m)\}_{m=1}^M$ of the ith slot at D is demodulated to obtain the corresponding soft channel values, as

$$L(\mathbf{y}_{iD}|\mathbf{x}_i) = 2 \cdot \Re\left\{\frac{\mathbf{y}_{iD} h_{iD}^*}{\sigma^2}\right\} \tag{4}$$

where the notations $L(\cdot)$ and $\Re(\cdot)$ denote the Log-Likelihood Ratio (LLR)[3] and a function that takes the real part of its argument, respectively, and $*$ indicates complex conjugation.

The soft channel outputs $L(\mathbf{y}_{iD}|\mathbf{x}_i)$ for the ith slot, are iteratively decoded by the decoder of the SCCC with the Log-MAP algorithm [23]. The estimated sequence $\hat{\mathbf{u}}_i$ of $\mathbf{u}_i$ is obtained by making binary hard decision on the *a posteriori* LLR $\{L(u_i(k)|\mathbf{y}_{iD})\}_{k=1}^K$ output from the decoder of C_S, when no relevant increase in LLR is obtained by iterations.

The sequences $\hat{\mathbf{u}}_i$ are CRC-decoded for error detection after completing the iterative decoding of the SCCC, and the

[3] $L(x) = \ln \frac{\Pr(x=1)}{\Pr(x=0)}$, where $\Pr(\cdot)$ denotes the probability of its argument.

decoding results for each user are stored in an N-bit identifier vector $\mathbf{F} = \{f(i)\}_{i=1}^{N}$, where

$$f(i) = \begin{cases} 0, & \hat{\mathbf{u}}_i = \mathbf{u}_i \\ 1, & \hat{\mathbf{u}}_i \neq \mathbf{u}_i \end{cases} \tag{5}$$

and a set $\mathcal{F}$ is defined as

$$\mathcal{F} = \{i : f(i) = 1\}. \tag{6}$$

If $\mathcal{F} \neq \phi$, D sends to R an redundancy-retransmission request with the vector $\mathbf{F}$ via the feedback channel and attempts to recover the information sequences decoded in error with additional redundancy forwarded from R.

As shown in Fig. 1, once receiving the retransmission request, the relay R performs network coding by taking a sequence-by-sequence XOR-operation, notated as $\bigoplus$, over the received estimates of the information sequences specified by $\mathbf{F}$ even though the specified estimates may contain errors, as

$$\mathbf{u}_R = \bigoplus_{\forall_j \in \mathcal{F}} \widetilde{\mathbf{u}}_j. \tag{7}$$

The relay node R then re-encodes the interleaved version of the network-coded bit sequence $\mathbf{u}_R = \{u_R(k)\}_{k=1}^{K}$ by using a rate-K/M RSC encoder C_R, and finally, the corresponding RSC-coded bit sequence $\mathbf{x}_R = \{x_R(m)\}_{m=1}^{M}$ is forwarded to D using BPSK modulation as additional redundancy.

B. Decoding scheme and algorithm of JANCC

Fig. 2 shows a factor graph representation of the proposed decoding scheme of JANCC, where C_S^{-1} and C_R^{-1}, respectively, indicate the RSC decoders corresponding to C_S and C_R used in the source nodes and R. The notations L_a and L_e shown in Fig. 2 denote $a\ priori$ and $extrinsic$ LLR of their argument variables, respectively. Once D receives additional redundancy forwarded from R, the decoding of JANCC is initiated to recover the information sequences decoded in error at D via the SD links.

As shown in Fig. 2, the LLR updating function $f_c(\cdot)$ [20] is utilized in the proposed JANCC decoding scheme to obtain the updated LLR sequence $\mathfrak{L}'$, as

$$\begin{aligned} \mathfrak{L}'(k) &= f_c(\mathfrak{L}(k),\, p_{nc}) \\ &= \ln \frac{(1-p_{nc}) \cdot e^{\mathfrak{L}(k)} + p_{nc}}{(1-p_{nc}) + p_{nc} \cdot e^{\mathfrak{L}(k)}} \end{aligned} \tag{8}$$

where $\mathfrak{L}$ represents the input LLR sequence to be updated by the function $f_c(\cdot)$, and p_{nc} is defined as

$$p_{nc} = \frac{\sum_{k=1}^{K} |u_R(k) - u_{\oplus}(k)|}{K} \tag{9}$$

where the sequence $\mathbf{u}_{\oplus}$ is generated by the source nodes specified by $\mathbf{F}$ as

$$\mathbf{u}_{\oplus} = \bigoplus_{\forall_j \in \mathcal{F}} \mathbf{u}_j. \tag{10}$$

The knowledge of the bit-flipping probability p_{nc} is exploited during the decoding process of JANCC in the LLR updating function $f_c(\cdot)$ to avoid the error propagation if one/some of the sequences $\widetilde{\mathbf{u}}_j$ obtained at R is/are erroneous. It should be emphasized that the probability p_{nc} can be estimated only at D without having to involve any higher layer protocols, as [24, eq. (9)]

$$\begin{aligned} \hat{p}_{nc} &= G(L_e(\Pi_R[\mathbf{u}_{\oplus}]),\, L_e(\Pi_R[\mathbf{u}_R]),\, \mathcal{G}) \\ &= G(L_e(\mathbf{u}_{\oplus}),\, L_e(\mathbf{u}_R),\, \mathcal{G}) \\ &= \frac{1}{|\mathcal{G}|} \sum_{\forall_g \in \mathcal{G}} \Pr(u_{\oplus}(g) = 1) \Pr(u_R(g) = 0) \\ &+ \Pr(u_{\oplus}(g) = 0) \Pr(u_R(g) = 1) \\ &= \frac{1}{|\mathcal{G}|} \sum_{\forall_g \in \mathcal{G}} \frac{e^{L_e(u_{\oplus}(g))}}{\left(1 + e^{L_e(u_{\oplus}(g))}\right)} \frac{1}{\left(1 + e^{L_e(u_R(g))}\right)} \\ &+ \frac{1}{\left(1 + e^{L_e(u_{\oplus}(g))}\right)} \frac{e^{L_e(u_R(g))}}{\left(1 + e^{L_e(u_R(g))}\right)} \\ &= \frac{1}{|\mathcal{G}|} \sum_{\forall_g \in \mathcal{G}} \frac{e^{L_e(u_{\oplus}(g))} + e^{L_e(u_R(g))}}{\left(1 + e^{L_e(u_{\oplus}(g))}\right)\left(1 + e^{L_e(u_R(g))}\right)} \end{aligned} \tag{11}$$

where $\hat{p}_{nc}$ is the estimated value of the probability p_{nc}, and $\Pi_R[\cdot]$ denotes interleaving by Π_R. The set $\mathcal{G}$ is defined as

$$\mathcal{G} = \{g : |L_e(u_{\oplus}(g))| \geq T\} \tag{12}$$

with T representing a threshold value. However, since the SD links suffer from block fading, we modified [24, eq. (9)] as follows: the value of T decreases during every iterative operation of the loop until a sufficiently large number of $L_e(u_{\oplus}(g))$ in the sequence $\mathbf{u}_{\oplus}$ is guaranteed (three-quarter of the entire sequence-length at least in this paper). $\mathbf{Algorithm 1}$ summarizes the decoding process of JANCC, where $\sum\boxplus$ and $\Pi_R^{-1}[\cdot]$ represent the boxplus operation [25] and de-interleaving by Π_R.

IV. Numerical results

In this section we provide the results of the simulations conducted to evaluate the performance of the developed energy-efficient orthogonal MARC system combined with the proposed JANCC techniques, which is referred to as DDEX-JANCC. In the simulations, the length of the information sequence K is 1024 bits, and the number of source nodes and retransmission are three and one, respectively. The RSC encoder C_S, C_R and ACC with the generator polynomials (G_r, G) are $(07, 05)$, $(07, 05)$ and $(03, 02)$, respectively, where the generator polynomial is expressed in an octal form and G_r specifies the feedback polynomial. The code rate K/M of C_S and C_R is 1/2, and the Log-Map algorithm is used in all the decoding process. The iterations I, interval ϵ, ratio ρ, threshold $T^{(0)}$ and times n used in $\mathbf{Algorithm\ 1}$ are set to 10, 0.05, 3/4, 3 and 10, respectively.

Two other alternative orthogonal MARC systems are also provided in the simulations for comparisons. One system uses the DDEX detection strategy while the other performs the

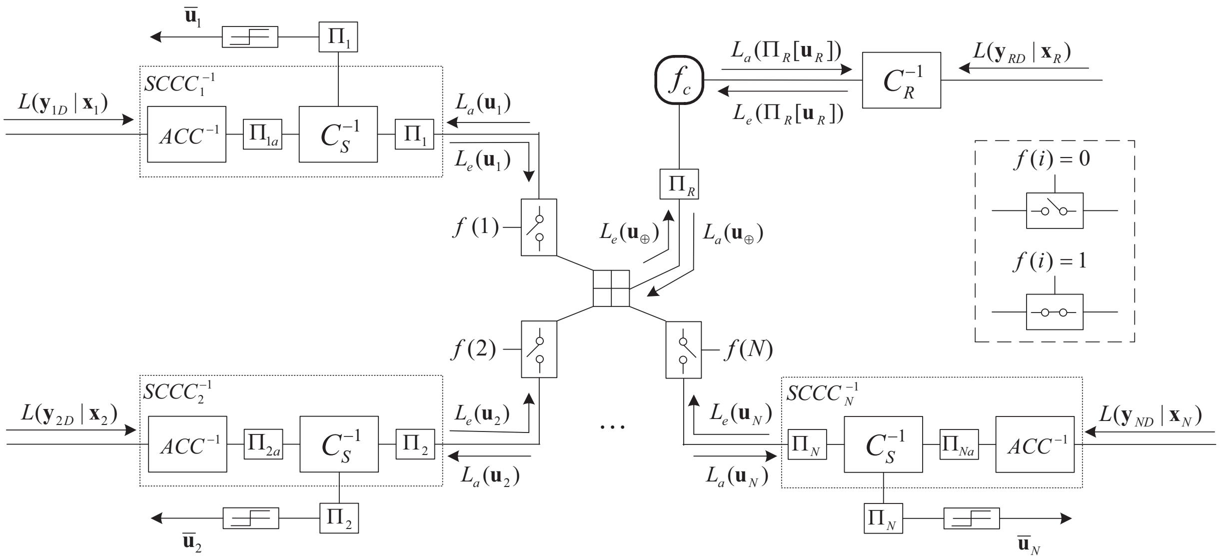

Fig. 2. Proposed decoding scheme of JANCC represented by factor graph, where ACC^{-1} and $SCCC_i^{-1}$ denote the ACC decoder and the decoder of the SCCC applied by S_i, respectively.

Algorithm 1: Decoding process of JANCC

Pre-defined: iterations I, interval ϵ, ratio ρ, threshold $T^{(0)}$, times n
Input: $L_e(\mathbf{u}_j),\ \forall_j \in \mathcal{F}$
Initialization: $\hat{p}_{nc} = 0.25$
for 1 **to** I **do**
  $L_e(\mathbf{u}_\oplus) = \sum_{\forall_j \in \mathcal{F}} \boxplus L_e(\mathbf{u}_j)$;
  for $l = 1$ **to** n **do**
    Find $\forall_q$ such that $|L_e(u_\oplus(q))| > T^{(l-1)}$;
    Store $\forall_q$ to set $\mathcal{Q}$;
    if $|\mathcal{Q}| \geq \rho \cdot \# L_e(\mathbf{u}_\oplus)$ **then**
      Exit **for**;
    end
    $T^{(l)} = T^{(l-1)} - \epsilon$;
    if $T^{(l)} \leq 0$ **then**
      Store all the indexes of $L_e(\mathbf{u}_\oplus)$ to set $\mathcal{Q}$;
      Exit **for**;
    end
  end
  $L_a(\Pi_R[\mathbf{u}_R]) = f_c\left(L_e(\Pi_R[\mathbf{u}_\oplus]), \hat{p}_{nc}\right)$;
  Calculate $L_e(\Pi_R[\mathbf{u}_R])$ by C_R^{-1};
  $\hat{p}_{nc} = G(L_e(\Pi_R[\mathbf{u}_\oplus]),\ L_e(\Pi_R[\mathbf{u}_R]),\ \mathcal{Q})$;
  $L_a(\mathbf{u}_\oplus) = \Pi_R^{-1}[f_c\left(L_e(\Pi_R[\mathbf{u}_R]), \hat{p}_{nc}\right)]$;
  for *all* $j \in \mathcal{F}$ **do**
    Calculate $L_a(\mathbf{u}_j)$ by boxplus operation;
    Feed $L_a(\mathbf{u}_j)$ to $SCCC_j^{-1}$;
    Calculate $L_e(\mathbf{u}_j)$ by $SCCC_j^{-1}$ with I iterations;
  end
end
Calculate $\bar{\mathbf{u}}_j,\ \forall_j \in \mathcal{F}$;

iterative decoding of the SCCC at R to obtain the sequences $\widetilde{\mathbf{u}}_i$. The JNCC technique [11] based on the conventional DF strategy, referred to as DFJNCC[4], is applied by both systems after obtaining $\widetilde{\mathbf{u}}_i$. According to their detection strategy applied at R, we refer these two systems to as DDEX-DFJNCC and SCCC-DFJNCC, respectively. The outage probability for the orthogonal MARC systems with the conventional DF strategy is numerically calculated by Monte Carlo methods, where we generated an enough number of random fading coefficients (h_{iR}, h_{iD} and h_{RD}) and measured the probability that the conditions provided in [11, eqs. (4)-(6)] are not satisfied.

The structure for all the orthogonal MARC systems are assumed to be symmetric in geometric gain where all the SR links have the same average SNR (Γ_{iR} = constant $\forall_i$) and all the SD links as well (Γ_{iR} = constant $\forall_i$). Finally, we define FER as follows in this paper: number of the information sequences which cannot be correctly decoded at D even with the help of R, divided by the total number of the sequences transmitted by all the source nodes.

Fig. 3 demonstrates the FER performance when $\Gamma_{iR} = \Gamma_{iD} + 0.5$ dB. First of all, we investigate the effect of the detection technique applied at R, assuming the conventional DF strategy. For the DDEX-DFJNCC system, as can be observed in Fig. 3, there is roughly a 3 dB loss in average SD SNR at FER = 10^{-2} compared with the SCCC-DFJNCC system. The loss is due to the fact that DDEX only extracts the estimates of the information sequences output from DD at R. However, if DDEX is combined with the proposed JANCC and its corresponding decoding techniques, i.e., DDEX-JANCC, the loss can be reduced to only 1.5 dB by utilizing the erroneous estimates of the transmitted source information received at R.

Furthermore, it can also be observed in Fig. 3 that by employing the proposed JANCC decoding algorithm

[4]For fair comparisons, the encoder of [11, Fig. 2] is modified by replacing the Turbo Encoder with C_R. In addition, the interleaver Π_R is added and placed between the XOR-operation and C_R.

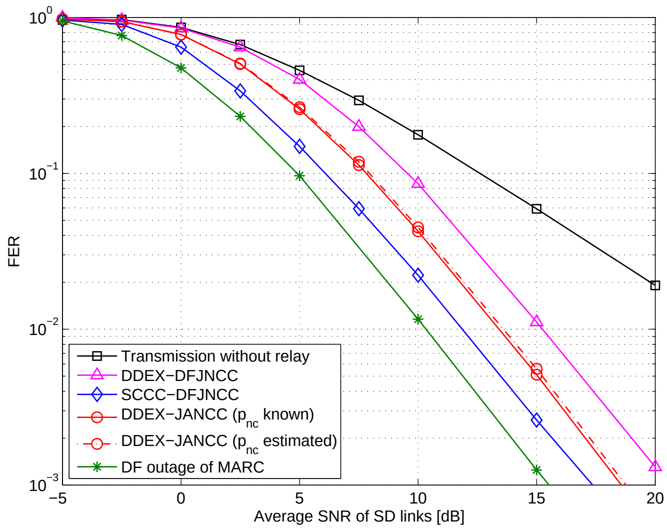

Fig. 3. FER performance when $\Gamma_{iR} = \Gamma_{iD} + 0.5$ dB, $\Gamma_{RD} = 20$ dB, and the number of source nodes $N = 3$.

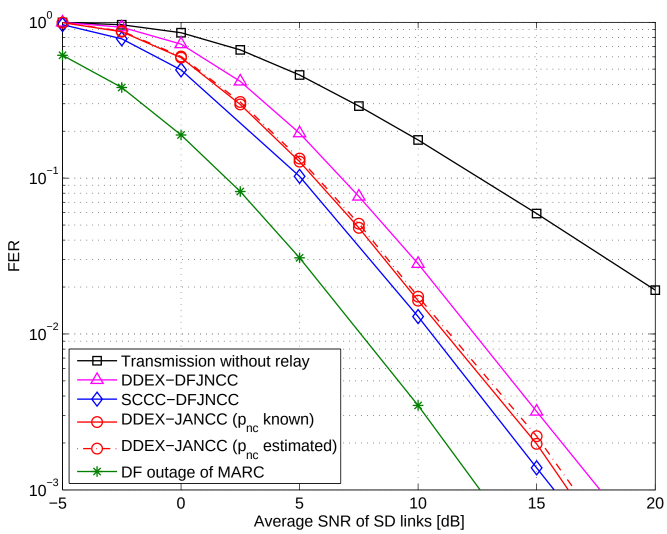

Fig. 4. FER performance when $\Gamma_{iR} = \Gamma_{iD} + 6.5$ dB, $\Gamma_{RD} = 20$ dB, and the number of source nodes $N = 3$.

(**Algorithm1**), the FER performance of DDEX-JANCC with the estimated bit-flipping probability $\hat{p}_{nc}$ is very close to the FER curve with the probability p_{nc} being known at D. In fact, this observation, together with the application of low-complexity DDEX at R, makes the DDEX-JANCC system practical in exchange for a 1.5 dB loss in average SD SNR, and a significant reduction in power consumption can be achieved due to low computational complexity required.

A. Impact of the SR link quality

In order to consider the impact of the quality of the SR links to the FER performance of the DDEX-JANCC system, another scenario was tested where $\Gamma_{iR} = \Gamma_{iD} + 6.5$ dB. It can be clearly observed in Fig. 4 that the gap in FER between the DDEX-DFJNCC and SCCC-DFJNCC systems is reduced, because the better quality of the SR links achieves the higher accuracy of the sequences $\tilde{\mathbf{u}}_i$ obtained at R, even by using the DDEX strategy. The DDEX-JANCC system can achieve 1 dB gain over DDEX-DFJNCC at FER = 10^{-2}, and only 0.5 dB away from SCCC-DFJNCC. However, the FER performance of the DDEX-JANCC system is roughly 3.5 dB away from the DF outage probability [11]. This observation indicatively means that the optimal code design for the SR links is left as a future study, when the quality of the SR links is good.

B. Computational Complexity Evaluation

We also make a comparison between the DDEX-JANCC and SCCC-DFJNCC systems in terms of computational complexity. The main difference between the two systems is due mainly to the detection strategy applied at R, so we calculate the number of addition (ADD), multiplication (MUL) and comparison (COMP) operations needed to obtain one estimated information sequence $\tilde{\mathbf{u}}_i$, where all the operations are on real numbers.

It is assumed $\tilde{\mathbf{u}}_i$ is obtained by performing the iterative decoding of the SCCC on the received vector $\mathbf{y}_{iR}$, where the Log-MAP algorithm is used on the inner and outer codes with memory length m_1 and m_2, respectively. The number of operations needed per bit in the Log-MAP decoding algorithm is provided in [23, Sec. 4.1]. Since the lengths of sequences decoded by the inner and outer decoders are M and K bits, respectively, the required number of operations per sequence of each constituent code is approximately M and K times higher, respectively. The total computational cost for the iterative decoding of the SCCC per iteration is obtained by summing the number of operations in the decoding of both codes, and thus, $(15 \cdot 2^{m_1} + 9) \cdot M + (15 \cdot 2^{m_2} + 9) \cdot K$ ADDs, $8 \cdot M + 8 \cdot K$ MULs and $(5 \cdot 2^{m_1} - 2) \cdot M + (5 \cdot 2^{m_2} - 2) \cdot K$ COMPs in total are required.

However, when using the DDEX strategy, only one complex multiplication per bit, equivalent to two ADDs and four MULs, is required by the DD strategy, and since $\mathbf{y}_{iR}$ is an M-bit sequence, $2M$ ADDs and $4M$ MULs in total are required in the detection of $\mathbf{y}_{iR}$. The sequence $\tilde{\mathbf{u}}_i$ is simply extracted from the output of DD and thus no operations are required.

It is clear that the required number of operations in each category in SCCC decoding is much higher than that in DDEX, where the cost for the correction function used in the Log-MAP algorithm is not considered. In addition, assuming ADD, MUL and COMP have equal complexity, with $m_1 = 1$, $m_2 = 2$, $K/M = 1/2$ and 10 iterations set in this paper, the complexity of SCCC decoding is at least 170 times higher than DDEX, which leads to significant power saving for computation at R.

C. Average throughput

For the proposed JANCC strategy, unlike DFJNCC, the specified estimates of the information sequences $\tilde{\mathbf{u}}_j, \forall_j \in \mathcal{F}$, are, regardless of whether they are correct or not, always jointly network-channel coded at R and forwarded to D when R received the retransmission request from D. Hence, in order to identify the probability for recovering the information sequence correctly at D with applying DFJNCC and JANCC at R, we also evaluate the average throughput of all the orthogonal MARC systems used in the simulations. Table I

TABLE I
ACHIEVED THROUGHPUT WITH/ WITHOUT RETRANSMISSION.

	DFJNCC										JANCC					
D sends request	No	Yes				Yes					No	Yes				
R forwarding	No					Yes					No	Yes				
correctly decoded msgs at D	N	$N-1$	$\cdots$	1	0	N	$N-1$	$\cdots$	1	0	N	N	$N-1$	$\cdots$	1	0
Achieved throughput	1	$\frac{N-1}{N}$	$\cdots$	$\frac{1}{N}$	0	$\frac{N}{N+1}$	$\frac{N-1}{N+1}$	$\cdots$	$\frac{1}{N+1}$	0	1	$\frac{N}{N+1}$	$\frac{N-1}{N+1}$	$\cdots$	$\frac{1}{N+1}$	0

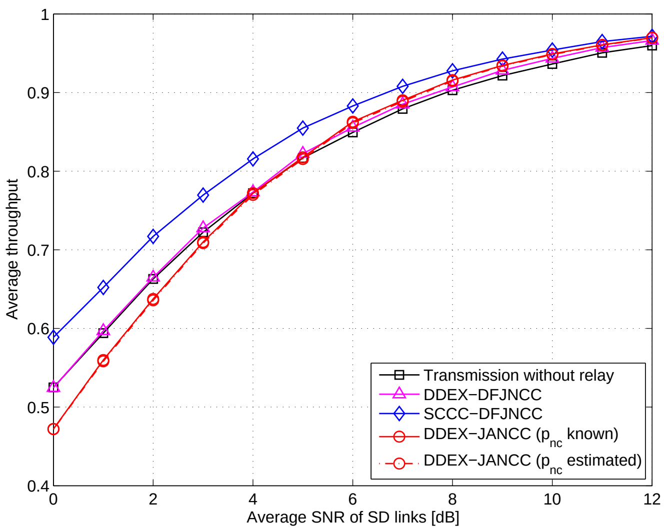

Fig. 5. Average throughput when $\Gamma_{iR} = \Gamma_{iD} + 0.5$ dB, $\Gamma_{RD} = 20$ dB, and the number of source nodes $N = 3$.

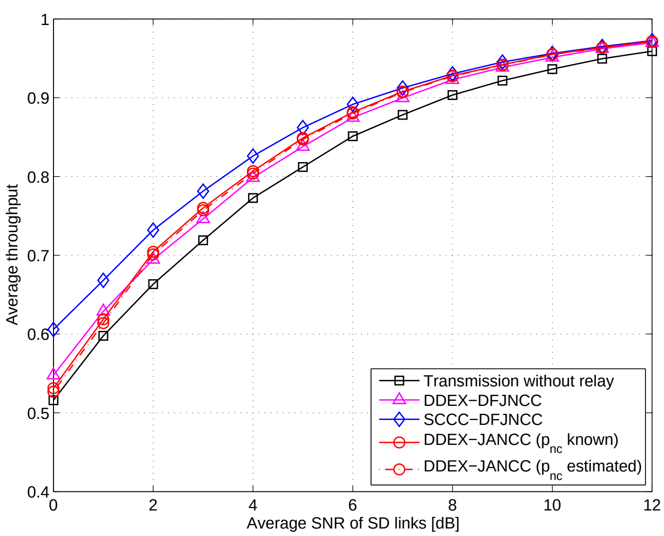

Fig. 6. Average throughput when $\Gamma_{iR} = \Gamma_{iD} + 6.5$ dB, $\Gamma_{RD} = 20$ dB, and the number of source nodes $N = 3$.

summarizes all the combinations for the cases that require retransmission request for applying DFJNCC and JANCC at R. The achieved throughput is defined as the number of correctly decoded information sequences at D totalling over all the source nodes, and the average throughput is calculated by averaging the achieved throughput under all the combinations according to the corresponding occurrence probabilities of those cases.

Fig. 5 shows the average throughput efficiencies of all the systems for $\Gamma_{iR} = \Gamma_{iD} + 0.5$ dB. The average throughput of the DDEX-JANCC system is even lower than the point-to-point transmission in the low SD SNR regime, which indicates the help of the proposed JANCC technique for the recovery of the information sequence at D is limited when the SR link quality is poor. The probability of $\tilde{\mathbf{u}}_j, \forall_j \in \mathcal{F}$ after the detection of DDEX containing a large amount of errors is relatively high when the quality of the SR links is poor, and thus, the bit-flipping probability between $\mathbf{u}_\oplus$ and $\mathbf{u}_R$ increases if any one of the sequences $\tilde{\mathbf{u}}_j$ contains a large amount of errors, which decreases the correction capability of JANCC decoding.

As the quality of the SR links improves, as shown in Fig. 5 and Fig. 6, the performance of the DDEX-JANCC system is apparently improved and outperforms the performance of DDEX-DFJNCC in terms of the average throughput efficiency. Furthermore, the average throughput of the DDEX-JANCC system asymptotically approaches to that with SCCC-DFJNCC, as shown in Fig. 6. Therefore, it can be concluded that the average throughput efficiency of the DDEX-JANCC system depends on the quality of the SR links.

V. CONCLUSION

This paper has investigated the developed energy-efficient orthogonal MARC system. A low-complexity and non-coherent detection strategy DDEX was applied at the relay R to reduce the energy consumption. The proposed JANCC and its corresponding decoding techniques were employed to utilize the erroneous estimates output from DDEX. A vector is constructed in the JANCC technique to identify the indexes of the source nodes whose information sequences are decoded in error at the destination D. The relay R performs network coding only on the estimates specified by the vector when receiving the retransmission request, which aims to avoid unnecessary erroneous estimates being network coded. The bit-flipping probability p_{nc} is observed between the two sequences, one is the network-coded sequence sent from R, and the other is their corresponding XOR-ed information sequence obtained at D. The proposed JANCC decoding algorithm estimated and exploited the probability p_{nc} to update the Log-Likelihood Ratio during the iterative decoding process. In the case of the system setup assumed in this paper, computational complexity of the DDEX strategy is at least 170 times lower than the iterative decoding of the SCCC performed at R, in exchange for only a $0.5-1.5$ dB loss in the FER performance. However, a significant reduction in power consumption can be achieved due to low computational complexity required and the elimination of channel estimation, which is suitable for the relaying systems where the availability of the resources is limited.

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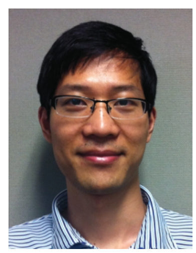

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