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Network-coded SIR-based distributed coding scheme: A new soft estimate modelling and performance analysis

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ABSTRACT

In this paper, we consider a multiple access relay channel (MARC) that operates in the decode and forward mode with network-coded soft information relaying (NC-SIR). We show that the combination of channel coding and NC-SIR in the MARC can be seen as a distributed coding scheme (DCS). In order to mitigate the error-propagation at the relay, we propose a new method for modelling the log-likelihood-ratio (LLR)-based soft estimated symbols at the output of the BCJR encoder. The calculation of the received LLRs at the destination is derived according to the proposed model. Moreover, a virtual one-hop link, the equivalent to the sources–relay–destination channels, is provided in terms of signal-to-noise ratio and related statistic. This allows us to give a tractable analysis on the bit error rate (BER) performance. The expression of the pairwise error probability under fully interleaved Rayleigh fading channels and an upper bound on the BER are derived analytically. Several simulation results show that the NC-SIR-based DCS using the proposed model outperforms those using other well-known models in terms of BER performance. Moreover, simulation results are presented to demonstrate the accuracy of the proposed bound for different relay positions between source and destination nodes.

1. Introduction

In network coding (NC) users are allowed to process the received message by a network coding operation [1]. Due to the broadcast nature of the wireless medium, NC has been regarded in wireless networks such as ad hoc and wireless sensor networks to enhance the available throughput [2], energy efficiency [3], robustness and security [4]. NC can suppress the bandwidth resource assigned to the relay transmission and hence increase the spectral efficiency of cooperative communications. It has been applied in conjunction with several relaying strategies such as the amplify-and-forward (AF) protocol [5] and decode-and-forward (DF) protocol [6] which have laid the foundation of relaying protocols. A well-known scheme that provides network-coded cooperation (NCC) is the multiple-access relay channel (MARC) which can be used for the cooperation of two source nodes to a destination with the help of a relay node. Applying the DF strategy, the relay decodes the two received sequences from the source nodes and re-encodes the network-coded estimates before forwarding them to the destination. The achievable diversity order of NCC was investigated in recent papers [7,8]. In [9], a joint network and channel coding (JNCC) scheme was proposed to achieve channel coding gain and spatial diversity. In [10], the performance analysis of a NCC scheme with channel coding and adaptive DF-based relaying is studied.

In this paper, we consider an NCC scheme in the MARC. The coexistence of channel coding and NC in the MARC is considered as a distributed coding scheme (DCS). The transmitted sequence from the relay provides an extra redundancy which is involved in a joint network and channel decoding (JNCD) at the receiver where all sources involved in the cooperation process benefit. However, DCS features require an error-free decoding at the relay. This requirement cannot be guaranteed in practice. A lot of approaches are proposed in the literature to deal with the erroneous decoding at the relay. In [11], the authors proposed some adaptive relaying schemes based on DF with a cyclic redundancy check (CRC) code at the relay. In [12], the case of erroneous decoding at the relay is addressed by means of a switching between the AF and DF strategies. In [13,14], the hard estimates at the relay are encoded with the conventional DF protocol, while at the destination a limiter function is employed during iterative decoding.

One of the most effective approaches proposed to address the problem of error propagation from the relay is the soft information relaying (SIR), where the *a-posteriori* soft-in/soft-out (SISO) decoded sequences are re-encoded by means of a relay soft encoder

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(RSE). The SIR is applied to incorporate the forwarded residual errors from the relay, and hence, we consider the SIR-based channel-network-coded cooperation as a DCS which is referred to as NC-SIR-DCS. For the calculation of the log-likelihood-ratios (LLRs) at the destination, the relationship between the forwarded soft estimated symbols (SESs) from the relay and the correct source symbols should be modelled. In [15], the *soft noise* model (SN-M) is presented, where the output LLRs of the RSE are mapped to soft bits by means of a tanh(LLR/2) operator and the so-called *soft noise* is modelled as non-zero-mean Gaussian noise. In [16], the *soft fading* model (SF-M) was presented, where the soft errors were described as fading coefficients. In [17,18], the authors proposed the *soft scalar* model (SS-M), where the soft symbols are modelled by means of a *soft error* and a *soft scalar* equivalent to a fading coefficient. The estimation of the models statistical parameters in [15–18] requires the knowledge of the transmitted symbols. For the LLRs calculation at the destination, the statistical parameters are either computed offline or estimated by means of training sequences. However, it is of interest to work with models whose parameters are determined online and without any additional cost. To the best of the authors knowledge, there is no closed form solution for the probability density function of the RSE output LLRs. The works in [19] and [20] have shown that the RSE output LLRs do not follow the exact Gaussian distribution especially for recursive soft encoder, even though the Gaussian assumption was employed in several works [21–24]. It is worth noting, that in the proposed scheme, the interleaved *a-posteriori* LLR sequences from the relay SISO decoders are extra network-coded before entering to the RSE, and hence, it is convenient to examine the distribution of the RSE output LLRs. In this paper, we prove, by means of the Kolmogorov–Smirnov (K–S) normality test [25] and the normal quantile–quantile (Q–Q) plot techniques, that the output LLRs of the non-recursive BCJR encoder, under fully interleaved Rayleigh fading channel at the different links, are not Gaussian. We note that, the K–S normality test and the normal Q–Q plot are the most common techniques to test the normality of a data distribution. This induced us to propose a new LLR-based model to be involved in the LLRs calculation at the destination so as to achieve better bit error performance.

The main contribution of this paper is the compact representation of the channel-network-coded cooperative scheme in the MARC with SIR as a DCS leading to tractable bit error rate (BER) performance analysis. This is achieved by means of the proposed Rayleigh–Gaussian LLR-based model (RGL-M) where the output LLRs of the RSE are modelled as output LLRs of a Rayleigh fading channel with additive zero-mean Gaussian noise. The proposed model is valid under fully interleaved Rayleigh fading and binary phase shift keying (BPSK) signalling at the different links. The parameters of the proposed model are computed online and forwarded to the destination which is of practical interest. Accordingly, we demonstrate how to calculate the LLRs of the received signals at the destination. The adequacy of the RGL-M compared to the Gaussian LLR-based model (GL-M) and soft bit-based models is experimentally justified by the BER performance improvement. For the sake of comparison, we additionally present a soft bit-based model, involving Rayleigh distributed fading coefficients, which is referred to as Rayleigh–Gaussian soft bit-based model (RGSB-M). Based on the RGL-M, we derive the signal-to-noise ratio (SNR) of the one-hop link, the equivalent to the sources–relay–destination links. The statistic of the equivalent one-hop link SNR is approximated. Accordingly, the pairwise error probability (PEP) of the NC-SIR-DCS is derived with respect to the SNRs in the direct links and the SNR of the equivalent one-hop link. For the purpose of the union bound calculation, we distinguish the different error scenarios of the DCS component codewords. Simulation results show the adequacy of the proposed model and confirm the accuracy of the calculated bounds for different relay positions between source nodes and destination.

The rest of this paper is organized as follows. The transmission model is introduced in Section 2. Section 3 presents the channel-network-coded cooperative communication in the MARC as a DCS. In Section 4, we present the RGL-M and summarize some models to be compared with. The performance analysis is carried out in Section 5. In Section 6, we present simulation results. Section 7 concludes this paper.

2. Transmission model

We consider the MARC which consists of two transmitting sources S_1 and S_2, one relay R and one destination D as depicted in Fig. 1. A cooperation phase consists of three timeslots. In the first two timeslots, each source consecutively broadcasts a data message to the relay and to the destination. In the third timeslot, the relay forwards a network-coded signal to the destination. The relay employs DF relaying strategy. We assume that the two source nodes and the relay node transmit through wireless orthogonal channels operating in a half-duplex mode. Let $\mathbf{u}_i = (u_{i,1}, \ldots, u_{i,K})$ be the binary information sequence of the source S_i, $i = 1, 2$, where K is the information word length. In this work, the sources employ identical binary channel codes C_S of rate $R_S = K/N_S$, where N_S is the codeword length in both sources. Let $\mathbf{c}_i = (c_{i,1}, \ldots, c_{i,N_S})$ be the source codeword corresponding to the information word $\mathbf{u}_i$, $i = 1, 2$. The code bits of $\mathbf{c}_i$ are mapped into modulated sequence $\mathbf{x}_i$, $i = 1, 2$. For simplicity, we consider a BPSK modulation where the tth modulated symbol in $\mathbf{x}_i$ is given by

$$x_{i,t} = (1 - 2c_{i,t}), \quad 1 \le t \le N_s, \quad i = 1, 2. \tag{1}$$

The tth symbol within the received sequence $\mathbf{y}_{S_iR_X}$, $R_X \in \{R, D\}$, can be expressed as

$$y_{S_iR_X,t} = \sqrt{P_{S_iR_X}} h_{S_iR_X,t} x_{i,t} + n_{S_iR_X,t}, \quad 1 \le t \le N_S, \tag{2}$$

where $P_{S_iR_X}$ is the received signal power at the receiver node R_X, $h_{S_iR_X,t}$ is the instantaneous fading coefficient in the S_i–R_X link modelled as Rayleigh distributed random variable and $n_{S_iR_X,t}$ is the instantaneous additive noise which is modelled as zero-mean Gaussian random variable with variance σ_n^2, $i = 1, 2$. All channels are subject of fully-interleaved normalized Rayleigh fading with a scale parameter σ_h equal to $1/\sqrt{2}$. For a BPSK transmission the noise power is $\sigma_n^2 = BN_0/2$, where B is the bandwidth of the passband signal and $N_0/2$ is the power spectral density per dimension of the white Gaussian noise. Assuming Nyquist filters, with zero roll-off factor, leads to $\sigma_n^2 = N_0/(2T_s)$, where T_s is the

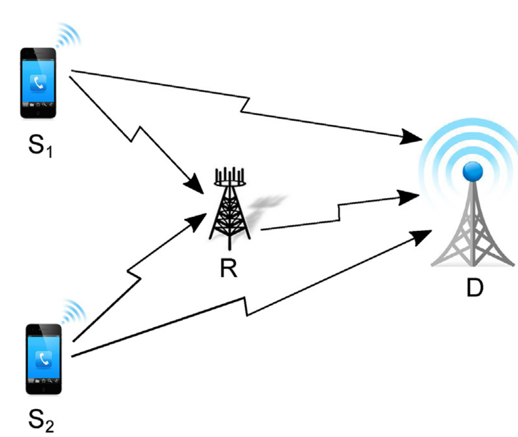

Fig. 1. A multiple-access relay channel with two source nodes, one relay and one destination.