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Block-Markov encoding with network coding for cooperative communications

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ABSTRACT

In this paper, we propose network coding as an operational implementation of information theoretic block-Markov coding for cooperative communications. This is a transmission strategy where users act as a relay for each other to help reliable recovery of the message at the destination(s). With analytical results, we show that even with this very simple implementation, we can outperform cooperative transmission schemes using legacy space–time (ST) and the repetition codes. We take outage probability and the diversity-multiplexing tradeoff curve as a performance measures to evaluate the gains offered by this so called cooperative communications using network coding scheme. The results show that, under block-fading channel, network coding based cooperative communications offers diversity order of 3 while ST and the repetition coding based cooperative transmission offers diversity order of 2 only. When the performance is compared in terms of diversity-multiplexing tradeoff, block-Markov codebook structure inspired, network coding based cooperative communications outperforms by 33%, in terms of multiplexing gain, both ST and the repetition coding based cooperative transmission schemes.

1. Introduction

Diversity was introduced to reduce the effects of unreliable nature of wireless communications [1]. The reason of this unreliability is the fact that the signal travelling from the source to the destination has to pass through many obstacles with varying degree of physical properties. These obstacles introduce the effects like scattering, reflection, refraction, and diffraction. These effects, in turn, introduce multipath fading. This faded signal, whose receive power level varies over time, frequency, polarization, and location is subject to noise and interference which result in unreliable bit decisions at the receiver. Diversity is an effective way to overcome, to some extent, these adverse effects on the received signals, where the receiver is provided with the multiple copies of the same transmitted signal. Cooperative diversity, along with time, frequency, and polarization, is a technique to achieve this goal. Cooperative communications is a way to provide cooperative diversity. In cooperative communications, transmitting users share their antennas to effectively develop a multiple-input multiple-output (MIMO) systems to achieve capacity and diversity gain [2,3]. The transmitting users not only send their own information, but also forward some information about the messages transmitted by other users in their vicinity. This cooperation among transmitting users not only improves the reliability of the received signal, but also offers improved rate regions for the cooperating users [4,1].

Information forwarded by the cooperating user may be in the form of re-transmission of the signal received from transmitting user, formally known as amplify-and-forward (AF) [5,6]. Alternatively, the cooperating user can also fully decode the message received from the transmitting user and forward re-encoded or compressed version of it to the destination. These forwarding strategies are called decode-and-forward (DF) [5,6] and compress-and-forward (CF) protocols [7], respectively. In addition to these basic protocols, many other protocols have been proposed and investigated with varying degree of complexity and performance. In this paper, we will restrict ourselves to DF protocol only.

The cooperative transmission gains are achievable if one follows the information theoretic code design used in the proof of the capacity regions of the cooperation diversity. Many efforts have been made to design the code to actually implement that information theoretic code book structure. Admirable work has been done by using low-density parity-check (LDPC) codes and the results are shown to be very close to the Shannon limit [8–10]. In addition to ST [11,12] and turbo codes [13,14], network coding for cooperative transmission was suggested in [15,16] without explicit indication of information theoretic code book structure.

In this paper, after a brief introduction of information theoretic block-Markov encoding, network coding is proposed as an efficient and cost effective solution to implement the codebook structure suggested by information theory. The performance is evaluated in term of outage probability and the resulting diversity-multiplexing tradeoff curve. The paper can be broadly divided into two parts. In the first part of the paper, the block-Markov encoding is explained highlighting, in particular, the structure of the codebook used to prove the achievability of the rates.

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In the second part of the paper, following the information theoretic code book structure, network coding is proposed as an operational implementation of the block-Markov encoding. Later, for block-fading channel, the outage performance of the network coded cooperative transmission is evaluated in comparison with cooperative communications using ST and the repetition codes. The results show that the network coded cooperation, following block-Markov encoding, offers diversity order of 3 while ST and the repetition coding based cooperative transmission offer diversity order of 2 only. Derived upper and the lower bounds on the diversity-multiplexing tradeoff also indicate the supremacy of this simple cooperative transmission scheme using network coding over ST and the repetition coding based cooperative communications.

The outline of the rest of the paper is as follows. In Section 2, after presenting the system model, we discuss the achievable rates and information theoretic code design to achieve those rates. In Section 3, network coding based refinement information is proposed to implement block-Markov codebook structure. As a performance measure, we present in Section 4, the outage probability and in Section 5, the diversity-multiplexing tradeoff curve for the proposed scheme, in comparison with ST and the repetition coding based cooperative communications. Finally, Section 6 gives the conclusion of our paper.

2. System model

Although, the concept of cooperative communications can be exploited in any wireless network both cellular and ad hoc, throughout this paper, a cellular network is taken into consideration.

A single cell, with two mobile station users u_1, u_2 and a single base station (BS), is considered. Each mobile station user has independent information to be sent to the destination. Note that throughout this paper the terms mobile station, transmitting users, and transmitting nodes are used interchangeably. The scenario for cooperative transmission is depicted in Fig. 1.

As seen, cooperative communications exploits the natural behavior of wireless communications where the signals transmitted from the transmitter not only reach the intended destination, but the receivers present on their way to the destination can also overhear this message.

The users who receive and detect each others' information are called *partners* like in [17–19]. We assume that the selection of the partners is done by the layers above physical layer, and we take two cooperating users for illustrating network coded cooperation. The selected partner acts as a relay for the transmitting user to send some additional information about its message to the destination. In this way, cooperative communications makes use of the unintended signals once considered as interference in the network. This setup differs from the pure relay channel [7] in the sense that each user not only performs relaying, but it has some information of its own to transmit as well.

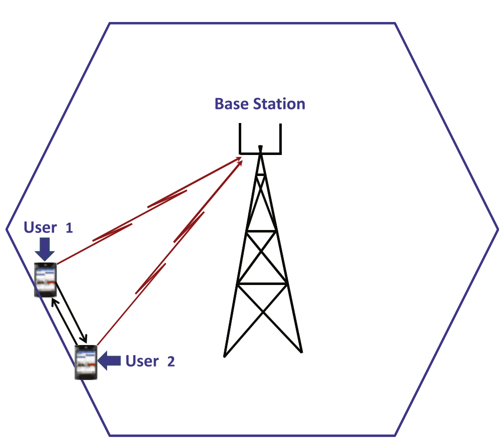

Fig. 1. Cooperative communications setup.

User terminals are capable of transmitting as well as receiving at the same time, i.e., they are considered to operate in full duplex mode. The resulting baseband channel model can be mathematically written as

$$y_0[k] = h_{1,0}x_1[k] + h_{2,0}x_2[k] + n_0[k], \quad (1)$$
$$y_1[k] = h_{2,1}x_2[k] + n_1[k], \quad (2)$$
$$y_2[k] = h_{1,2}x_1[k] + n_2[k]. \quad (3)$$

$y_0[k]$, $y_1[k]$ and $y_2[k]$ represent the signals received at the destination, i.e., at BS and the mobile users u_1 and u_2, respectively. x_i is the encoded message transmitted by the users u_i. n_j represent the additive noise at the receivers modeled as white complex Gaussian random variables with zero mean and N_o variance, where $j = 0, 1, 2$. Fading coefficients between transmitter i and receiver j are represented by $h_{i,j}$ and are modeled as zero mean complex Gaussian random variables with variance $\sigma^2_{i,j}$. The magnitude $|h_{i,j}|$ is Rayleigh distributed with probability density function (pdf)

$$P_X(x) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}. \quad (x \geqslant 0) \quad (4)$$

and the magnitude square $|h_{i,j}|^2$ follows the exponential distribution with pdf

$$P_X(x) = \lambda e^{-\lambda x}, \quad (x \geqslant 0). \quad (5)$$

An average transmission power constraint of P_i is imposed on the transmitted signal x_i, from the user u_i. Signal-to-noise ratio (SNR) is defined as

$$\gamma |h_{i,j}|^2, \quad (6)$$

where

$$\gamma = \frac{P_i}{N_o}.$$

2.1. Achievable rates with decode-and-forward transmission

For completeness, we re-iterate here the achievable rates for cooperative communications using DF relaying protocol by following theorem from [20]. For thorough understanding, the reader is referred to [20–23].

2.1.1. Achievable rates

The set of achievable rates for decode-and-forward transmission over a memoryless Gaussian multiple-access channel with cooperative diversity is given by the set of all (R_1, R_2) satisfying[1]

$$R_1 < \log\left(1 + \alpha_1 |h_{1,2}|^2 \gamma_{1,2}\right), \quad (7)$$
$$R_2 < \log\left(1 + \alpha_2 |h_{2,1}|^2 \gamma_{2,1}\right), \quad (8)$$
$$R_1 + R_2 < \log\Big(1 + \gamma_{1,0} + \gamma_{2,0} + 2\sqrt{(1-\alpha_1)(1-\alpha_2)|h_{1,0}|^2\gamma_{1,0}|h_{2,0}|^2\gamma_{2,0}}\Big) \quad (9)$$

for some $0 \leqslant \alpha_i \leqslant 1$, $i = 0, 1$, and $|h_{i,j}|^2$ being fixed and known both at the transmitter and receiver.

[1] All logarithms are taken to base 2, unless indicated explicitly.