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On the mutual information of relaying protocols

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ABSTRACT

The end-to-end performance metric for a conventional relay network with chase combining is the total Signal-to-Noise Ratio (SNR) delivered at the destination. However, the accumulated mutual information at the destination is the most suitable metric for a relay network which performs code combining (incremental redundancy) instead of chase combining at the destination. This paper investigates the accumulated mutual information acquired at the destination in an Amplify-and-Forward (AF), Decode-and-Forward (DF), and Coded Cooperation (CC) relay network. So far, the analytical comparison of the accumulated mutual information for the different relaying protocols is not reported in the literature. In this paper, it is proved analytically that the mutual information of a relay network with coded cooperation is always greater than or equal to the mutual information of decode-and-forward and amplify-and-forward for the case when all the relays can decode successfully. Moreover, it is also shown that the mutual information of a network with coded cooperation is always greater than or equal to that of a decode-and-forward relay network.

1. Introduction

In the future wireless networks, high data rates and ubiquitous access are the main focus of research. Moreover, multi-path propagation and less coverage at the cell edge are bottlenecks in achieving these high data rates and ubiquitous access. To transmit the signal from the source via relays to the destination [1,2] is one viable solution. Such a network is called cooperative relay network. In such a network, the signal from the source not only arrives through a direct link to the destination but also through intermediate nodes called relays. The signal transmitted from the source is captured by the intermediate nodes and they forward the signal to the destination. Most of the research in this domain [3,4] has assumed that the intermediate nodes (relays) operate in half-duplex (HD) mode. It means that they cannot transmit and receive simultaneously on the same frequency-band. More recently, a number of studies [5–7] have investigated the case when the relays operate in full-duplex modes. In this case, a relay can transmit and receive simultaneously using the same frequency-band or time-slot. Moreover, the intermediate node (relay) can also process the signal being received. Different processing techniques at the relay such as amplify-and-forward, decode-and-forward, and coded cooperation [8,2,9] have been investigated. Furthermore, the method of quantization at the relay and then forwarding the information is also provided in [10] and [11].

The end-to-end (from source to destination via relays) performance of a relay network can be measured through the total signal-to-noise ratio (SNR) provided at the destination after the combination of all of the received signals for relays using amplify-and-forward or decode-and-forward. For relays using coded cooperation, the total mutual information delivered at the destination is a suitable performance metric. The question is: Is the mutual information provided by a decode-and-forward relay network greater than the mutual information provided by a relay network with coded cooperation or amplify-and-forward for the considered relay network. This paper investigates to answer this question by using mathematical analysis. Moreover, mostly only SNR is considered and used as a performance criteria in conjunction with outage probability, bit-error-rate, or throughput in most of the literature [12,8,13,2,14] for the comparison of different relay networks. As stated above, SNR is not a suitable performance metric for relays with coded cooperation. The reason for this is the fact that when code is combined then extra mutual information instead of SNR are added while in chase combining SNR are added together.

The mutual information accumulation in the context of relay networks has been studied in [15–17]. However, the focus in these papers was on routing and energy efficiency. An analytical comparison of the mutual information of these relaying protocols is not reported. In this article, we compare analytically the mutual information of these protocols and provide the respective proofs.

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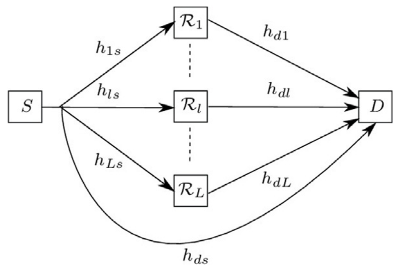

Fig. 1. Description of the relay network .

2. System model

A diagram depicting the concept of a relay network is shown in Fig. 1. In this network, the source S transmits its information to the destination D via the L relays $R_1, R_2, \ldots, R_L$ as well as via the direct link. Moreover, arbitrary modulation and arbitrary channel coding schemes with Rayleigh flat fading channel are considered. The effective channel coefficients h_{ls} and h_{ds} on source-lth relay link and source–destination link, respectively are assumed. Here, $l \in \mathcal{R} = \{1, 2, 3, \ldots, L\}$ holds. Moreover, additive white Gaussian noise is also assumed with variance σ_n^2 on each link. Similarly, h_{dl} is the effective channel coefficient on relay–destination link.

Here, we assume half duplex relaying in which the relay only receives first and then in the next time-slot it forwards the signal. First of all, the source transmits its information to the destination. As the channel is wireless, therefore, the nearby L relays also receive this information. During the transmission, the source encodes its k bits information $\mathbf{u}$ using an ideal code $\mathcal{C}$.[1] Later, the source uses arbitrary M-ary modulation to generate the sequence $\mathbf{x}_s$ and transmits the signal.

Afterwards, the received baseband signal at the lth relay from the source can be represented as

$$\mathbf{y}_{ls} = \sqrt{\alpha_s} \cdot a_{ls} \cdot h_{ls} \cdot \mathbf{x}_s + \mathbf{n}_{ls}. \tag{1}$$

In this paper, α_s and a_{ls} are used to represent the power used at the source and the path-loss coefficient due to the distance between the source and lth relay, respectively. Moreover, the noise $\mathbf{n}_{ls}$ is from an additive white Gaussian noise (AWGN) process with mean zero and variance σ_n^2. The signal obtained at the destination through the direct path from the source is

$$\mathbf{y}_{ds} = \sqrt{\alpha_s} \cdot a_{ds} \cdot h_{ds} \cdot \mathbf{x}_s + \mathbf{n}_{ds}. \tag{2}$$

Again, the noise $\mathbf{n}_{ds}$ is from an AWGN process with mean zero and variance σ_n^2 and a_{ds} is the path-loss coefficient due to distance, respectively.

The lth relay processes the received signal $\mathbf{y}_{ls}$ and transmits the signal $\mathbf{x}_{r_l}$.

At the destination, the equivalent received baseband signal from the lth relay can be written as

$$\mathbf{y}_{dl} = \sqrt{\alpha_l} \cdot a_{dl} \cdot h_{dl} \cdot \mathbf{x}_{r_l} + \mathbf{n}_{dl}. \tag{3}$$

The notation α_l and a_{dl} denote the power used at the relay and the path-loss coefficient, respectively. The noise sequence $\mathbf{n}_{dl}$ has identical statistics as the noise in (2).

The signal-to-noise ratio (SNR) which is obtained from the source–relay and source–destination links can be given as

$$\gamma_{ls} = \frac{\alpha_s \cdot a_{ls}^2 \cdot |h_{ls}|^2}{\sigma_n^2} \tag{4}$$

and

$$\gamma_{ds} = \frac{\alpha_s \cdot a_{ds}^2 \cdot |h_{ds}|^2}{\sigma_n^2} \tag{5}$$

respectively.

3. Relay forwarding techniques

At the relay, there exists possibility for multiple forwarding strategies such as amplify-and-forward, decode-and-forward, and coded cooperation [8,2,9]. In this section, these relaying techniques are discussed.

3.1. Amplify -and-forward

In this scheme of Amplify-and-Forward (AF) [2,18], the relay just scales the received signal and forwards it. The network with all relays using amplify-and-forward is called amplify-and-forward relay network. The signal forwarded from the lth relay during a time-slot of T_s symbols is

$$\mathbf{x}_{r_l} = \sqrt{\alpha_l} \cdot G_l \cdot \mathbf{y}_{ls}, \tag{6}$$

where, $G_l = \frac{1}{\sqrt{\alpha_s \cdot |h_{ls}|^2 + \sigma_n^2}}$ holds.

The received $\mathbf{y}_{ls}$ is scaled with the gain G_l so that the average transmit power is limited to α_l.

In AF, the relay does not need to successfully decode the signal. The benefit of this relaying scheme is the reduced hardware complexity due to the fact that the relay just scales the incoming signal and forwards it. However, the useful signal as well as the noise both are amplified. In the literature related to wireless communication, this forwarding technique is also known as non-regenerative relaying.

The total SNR received at the destination from the lth AF relay can be given as

$$\gamma_l = \frac{\gamma_{ls} \cdot \gamma_2}{\gamma_{ls} + \gamma_2 + 1}. \tag{7}$$

Here, γ_2 is given as

$$\gamma_2 = \frac{\alpha_l \cdot a_{dl}^2 \cdot |h_{dl}|^2}{\sigma_n^2}. \tag{8}$$

3.2. Decode -and-forward

In Decode-and-Forward (DF), if the relay can decode successfully the received signal, it re-encodes it using the same code as at the source and forwards it to the destination. Thus, the same coded sequence as used at the source is transmitted from the relay. A network with all relays doing decode and forward is called DF relay network. If the relay cannot decode successfully then it does not transmit at all and remain silent. In the case of successful decoding, the signal transmitted from the lth relay to the destination can be represented as

$$\mathbf{x}_{r_l} = \sqrt{\alpha_l} \cdot \mathbf{x}_s. \tag{9}$$

Finally, the SNR received per symbol at the destination from the lth relay can be given as

$$\gamma_l = \begin{cases} \frac{\alpha_l \cdot a_{dl}^2 \cdot |h_{dl}|^2}{\sigma_n^2} & \text{If the relay can decode successfully} \\ 0 & \text{Otherwise} \end{cases}. \tag{10}$$

3.3. Coded cooperation

In Coded Cooperation (CC) [9,19], the source and each of the relay transmit incremental redundancy (IR) [20,21]. Incremental

[1] Ideal coding scheme is explained later.