Modeling Cooperative Diversity in a Wireless Relay Channel

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Abstract

Cooperative diversity in wireless multi-hop networks is an attractive new way to increase throughput, reduce energy requirements and provide resistance to channel fading effects. Because of its distributed nature, this new form of diversity allows a network of relatively simple, single-antenna devices to achieve many of the celebrated advantages of physical antenna arrays. The objective of this work is to seek out and understand the various strategies for cooperative diversity and to develop a modeling framework in which these strategies can be evaluated and new strategies can be developed. In this paper we give a brief overview of multipath fading, describe a general three-node model for evaluating cooperative diversity in wireless networks and summarize existing cooperative diversity strategies.

1. Introduction

Multi-hop wireless networks enjoy many advantages over their more centralized counterparts. One particularly clever advantage that has begun to receive attention recently is their ability to achieve spatial diversity gains by allowing nodes in the network to cooperatively retransmit (i.e. relay) messages for neighboring nodes. As is the case with traditional, physical antenna arrays, these "distributed antenna arrays" combat multipath fading in wireless channels by providing receivers with essentially redundant signals over independent channels that can be combined to average individual channel effects. This form of spatial diversity, commonly known as cooperative diversity, not only improves the network's robustness to signal fading caused by multipath propagation but has also been shown to provide the network with higher bit rates, reduced energy requirements and improved access coverage [1-6].

The key advantage of cooperation is that it allows a network of relatively simple, inexpensive, single-antenna devices to achieve many of the celebrated advantages of physical antenna arrays. In addition, cooperative diversity can be readily combined with other forms of diversity, such as temporal and frequency diversity, to further exploit the available degrees of freedom in the wireless propagation environment and improve overall network performance.

Our primary goal is to review and analyze various approaches to cooperative diversity and construct a framework for modeling them and their effects on overall system outage probability.

2. Background

One of the most severe forms of interference plaguing wireless communication channels is the signal attenuation caused by multipath propagation effects, commonly known as multipath fading. Multipath fading occurs when a transmitted signal takes multiple paths to its destination and destructively interferes with itself (or more intuitively, delayed copies of itself) at the intended receiver. Figure 1 illustrates this for the simple case of a sinusoidal signal propagating over two signal paths.

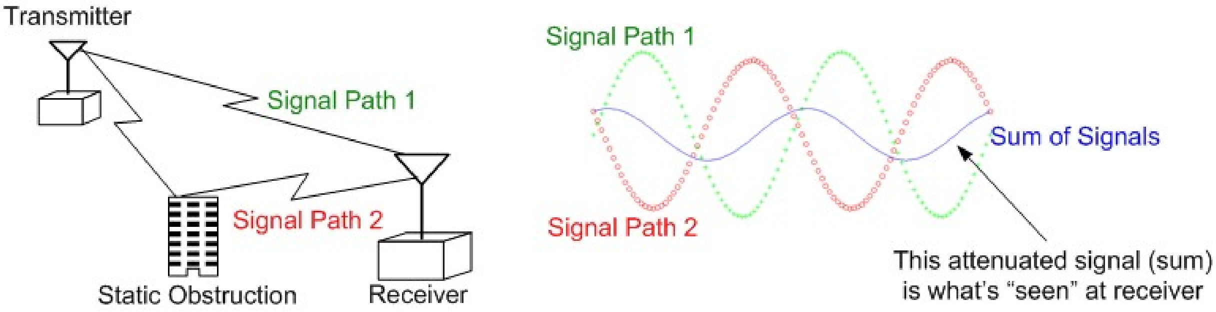


Figure 1: Multipath fading of a sinusoidal signal over two signal paths

"Diversity," as it applies to wireless transmissions, combats multipath fading by providing the receiver with redundant signal information through uncorrelated (i.e. diverse) channels thereby allowing the receiver to average individual channel effects. The most common forms of diversity are space, time and frequency; however, space and time diversity are the forms most readily exploited by cooperation.

- **Spatial diversity:** Spatial diversity is achieved by the transmission and/or reception of multiple copies of a signal from physically different points in space (i.e. multiple transmit and/or receive antennas). If an appropriate distance separates the points from where the signals are transmitted or received, then the characteristics of the channel are probabilistically uncorrelated and full diversity is obtained.

- **Temporal diversity:** Temporal or time diversity can be exploited by a channel coding strategy (i.e. adding redundant message bits) when the fading characteristics of the transmission channel correspond to a stationary and ergodic process whose structure emerges within a given coding interval. With the appropriate code, information loss due temporal variations in the channel caused by multipath fading can be detected and corrected.

3. System Model

The relay channel, proposed by Meulen in [7] and analyzed in [1], represents the most fundamental component of any cooperative wireless network. The model consists of a single source, destination and relay node. The source transmits a message that, due to the nature of wireless propagation, is received by both the destination and relay. Depending on the cooperation strategy employed by the relay node, it may do anything from simply amplifying the message signal to fully decoding and re-encoding the message before forwarding it to the destination. (Note: Despite this apparent range in cooperation strategies available to the relay, it has been these two extreme strategies, known simply as amplify-and-forward and decode-and-forward relaying, which have received the most attention to date.) A suitable model for our analysis is shown in Figure 2.

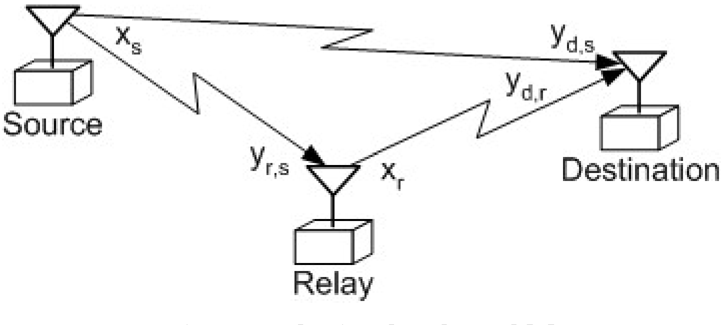


Figure 2: Classic relay channel [7]

Note that a slightly more general form of the relay channel is the symmetric case in which both source and relay have data to send. In this scenario, the roles of source and relay are simply exchanged for a given transmission period or channel; thus, the relay channel in Figure 2 is still applicable.

For simplicity of exposition, the individual links shown in Figure 2 are assumed to be orthogonal, narrowband wireless channels suffering from frequency nonselective fading and additive noise. A mathematical formulation of the discrete-time, baseband-equivalent channel model can be written as

$$\begin{aligned} y_{d,s}[n] &= a_{s,d} x_s[n] + z_{d,s}[n] \\ y_{r,s}[n] &= a_{s,r} x_s[n] + z_{r,s}[n] \\ y_{d,r}[n] &= a_{r,d} x_r[n] + z_{d,r}[n] \end{aligned} \tag{1}$$

where the fading coefficients $a_{s,d}$, $a_{s,r}$ and $a_{r,d}$, capture the effects of path-loss, shadowing and frequency nonselective fading in the source-destination, source-relay and relay-destination channels, respectively. The terms $z_{d,s}$, $z_{r,s}$ and $z_{d,r}$ capture the effects of receiver thermal noise and other forms of interference. The fading coefficients $a_{i,j}$ are modeled as independent zero-mean stationary complex jointly Gaussian random sequences so that their magnitudes $|a_{i,j}|$ are Rayleigh distributed (i.e. a Rayleigh fading channel) and the $z_{i,j}$ terms are modeled as white zero-mean complex Gaussian random sequences with variance N_0.

In many protocol-based cooperation strategies, the level of cooperation between the source and relay is decided by the instantaneous SNR of their shared link. We denote the SNRs for our model as $\gamma_{s,d}$, $\gamma_{s,r}$ and $\gamma_{r,d}$.

4. Cooperation Strategies

Many cooperation strategies based on the relay channel (and slight variations of it) have been proposed in recent years. The strategies typically fall into a subset of the following three general categories based on relay behavior: 1) amplify-and-forward, 2) decode-and-forward and 3) adaptive/protocol-based. These general strategies are described in Sections 4.2 through 4.4 after a brief discussion on methods of performance evaluation in Section 4.1.

4.1 Performance Evaluation

In order to gauge their effectiveness in combating multipath fading, cooperation strategies are typically evaluated based on some form of error probability at the destination. The most common metric used is outage event probability, which is defined as the probability that the received SNR falls below a given threshold. Other performance evaluation criteria include bit error rate, frame error rate and capacity bounds. In addition, when energy efficiency is a concern, strategies may be evaluated based on minimum SNR requirements for a given, fixed probability of error.

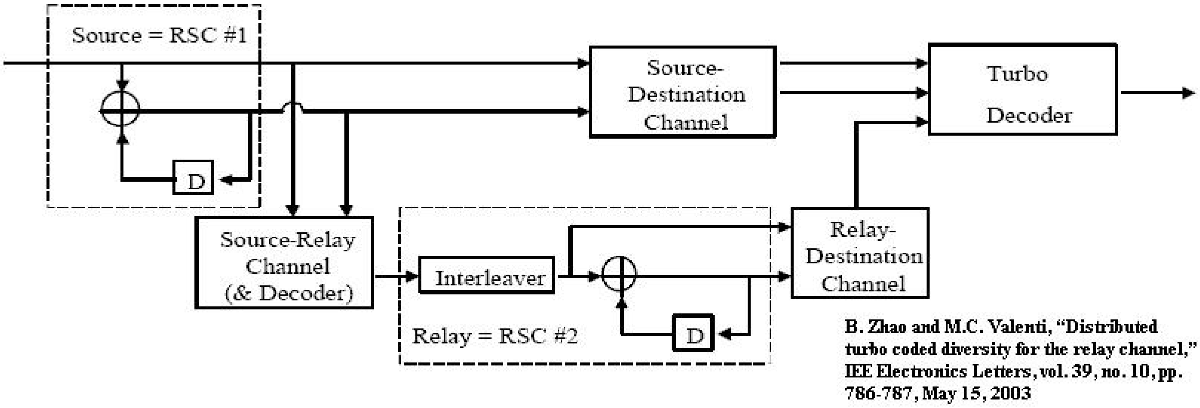
4.2 Amplify-and-Forward Relaying

The amplify-and-forward relay strategy represents the simplest way that a relay node may cooperate. Under this scheme, the relay simply buffers the source node's analog transmission over some predefined time interval (i.e. frame, codeword, etc. which is generally denoted as a "cooperation period") and retransmits an amplified copy of the signal during the following cooperation period. This approach has the negative side effect of amplifying the relay's received noise. However, it has been shown in [8-10] that this scheme still provides gains over non-cooperation in terms of outage probability and can even outperform decode-and-forward relaying in certain network geometries.

4.3 Decode-and-Forward Relaying

In the decode-and-forward scheme, the relay node fully decodes, re-encodes and retransmits the source node's message. The relay may re-encode the message with the same code (i.e. repetition codes or space-time codes as in [11]), re-encode with a completely different code or may participate in some form of distributed code construction whereby the source and relay cooperatively encode the source's message as introduced in [12]. In general, decode-and-forward outperforms amplify-and-forward relaying in cases where the relay can reliably decode the source node's message (i.e., a sufficiently large $\gamma_{s,r}$).

Zhao and Valenti present and analyze several decode-and-forward strategies based on a "distributed turbo code" in [13-16]. In their proposed strategies, the source and relay nodes cooperatively construct a distributed turbo code by introducing an interleaver into the relay node. Thus the source-destination path carries an uninterleaved encoding while the relay-destination path carries an interleaved encoding of the same data. The authors present simulation results indicating that the code performs close to information-theoretic bounds. A diagram of their proposed coding scheme is shown in Figure 3, where "RSC" is a Recursive Systematic Convolutional code, which is one of the components of a traditional turbo code.



B. Zhao and M.C. Valenti, "Distributed turbo coded diversity for the relay channel," IEE Electronics Letters, vol. 39, no. 10, pp. 786-787, May 15, 2003

Figure 3: Zhao and Valenti's "distributed turbo code" for coded cooperative diversity

4.4 Adaptive / Protocol-Based

Although much of the early work in cooperative diversity focuses on the amplify-and-forward and decode-and-forward schemes, all recent contributions have evolved into developing various protocols or adaptive cooperation schemes. These schemes are typically based on the fact that mutually cooperating nodes (i.e. the symmetric source-relay case) are able to estimate the fading coefficient and instantaneous SNR $\gamma_{s,r}$ of their shared channel to a high degree of accuracy. This allows cooperating nodes to make decisions about what type of strategy to employ dynamically. In other schemes, channel state information is fed back from the destination to further improve network adaptability and optimization.

Laneman *et al.* develop and analyze various low-complexity protocol-based strategies for cooperative diversity in [8-11]. In [10] they develop what are called “fixed cooperative” protocols for the amplify-and-forward and decode-and-forward relay strategies as well as adaptive protocols that use instantaneous SNR measurements to choose an appropriate protocol for a given time interval. They also develop protocols that take advantage of limited feedback from the destination node.

5. Modeling

The primary objective of this work is to develop a modeling framework, within a network simulation environment, in which the various protocols and strategies for cooperative diversity can be evaluated and new strategies can be developed. The framework will be evaluated initially on its ability to model an amplify-and-forward relay and in the sequel, on its successful demonstration of Valenti’s distributed turbo code [13]. An initial investigation suggests that National Instrument’s LabView and UC Berkeley’s Ptolemy-II are likely candidates for the simulation environment; however, additional evaluation of more traditional network simulators, such as NS-2 and OPNET, is underway.

Based on the system model developed in Section 3, our system can be modeled in software as a hierarchical simulation of Synchronous or Dynamic Dataflow nodes embedded in either a Discrete Event or Synchronous Dataflow network model.

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