Modeling Cooperative Diversity in a Wireless Relay Channel

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Abstract

Cooperative diversity is an attractive new way to increase throughput, reduce energy requirements and provide resistance to channel fading effects in wireless networks. Because of its distributed nature, this new approach to spatial 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 investigate 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 I present a Synchronous Dataflow (SDF) model for cooperative diversity in the wireless relay channel and an implementation designed in National Instruments' (NI) LabView development environment.

1 Introduction

Mobile, ad-hoc wireless networks enjoy many advantages over their more centralized counterparts. One particularly clever advantage 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 [1-4].

The key advantage of cooperation is that it enables a network of relatively simple, inexpensive, single-antenna devices to achieve the spatial diversity advantages of physical antenna arrays. Because of this, cooperation may have direct applications in current generation cellular telephone networks and high-speed data networks as well as sensor networks and future, hybrid voice/data networks.

Because of its distributed nature and the inherent difficulties imposed by wireless channels, investigating the effects of cooperation is a complex task. There are no existing implementations or executable models for investigating this new form of diversity.

The objective of this work is to investigate the various strategies for cooperative diversity and to develop a flexible software framework in which these strategies can be evaluated and new strategies can be developed. In this paper I present a Synchronous Dataflow (SDF) model for cooperative diversity in the wireless relay channel and an implementation constructed in National Instruments’ LabView development environment.

2 Background

2.1 Multipath Channels & Diversity

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 at the intended receiver.

"Diversity," as it applies to wireless transmissions, combats multipath fading by providing a receiver with redundant signal information through uncorrelated 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 can be exploited by a channel coding strategy (i.e. adding redundant 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.

2.2 The Relay Channel

The relay channel, proposed by Meulen in [5] 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. A suitable model for analysis is shown in Figure 1.

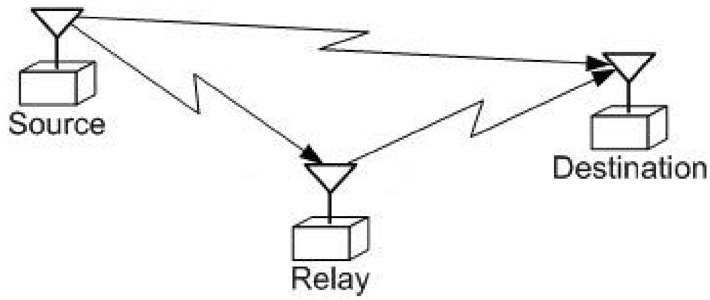

Figure 1: Classic relay channel [5]

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 1 is still applicable.

2.3 Cooperation Strategies

Many cooperation strategies based on the relay channel have been proposed in recent years. The strategies typically fall into one of the following three categories based on relay behavior.

1) Amplify-and-Forward: 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 [3,6,7] 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.

2) Decode-and-Forward: 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 [8]), 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 [4,9]. In general, decode-and-forward outperforms amplify-and-forward relaying in cases where the relay can reliably decode the source node's message.

3) Adaptive/Protocol-Based: Although early work investigated the previous two strategies almost exclusively, recent contributions have evolved into developing various protocols or adaptive cooperation schemes. These schemes are typically based on the fact that mutually cooperating nodes are able to estimate the fading coefficients and instantaneous signal-to-noise ratio 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.

3 Modeling

I model an instance of the relay channel (including the source, relay and destination nodes as well as all communication links connecting them) as a hierarchical SDF graph as illustrated in Figure 2. SDF is particularly useful for modeling communication and signal processing systems where decisions are generally not made based on data values and the quantity of data produced and consumed by each component is static and known *a priori* [10].

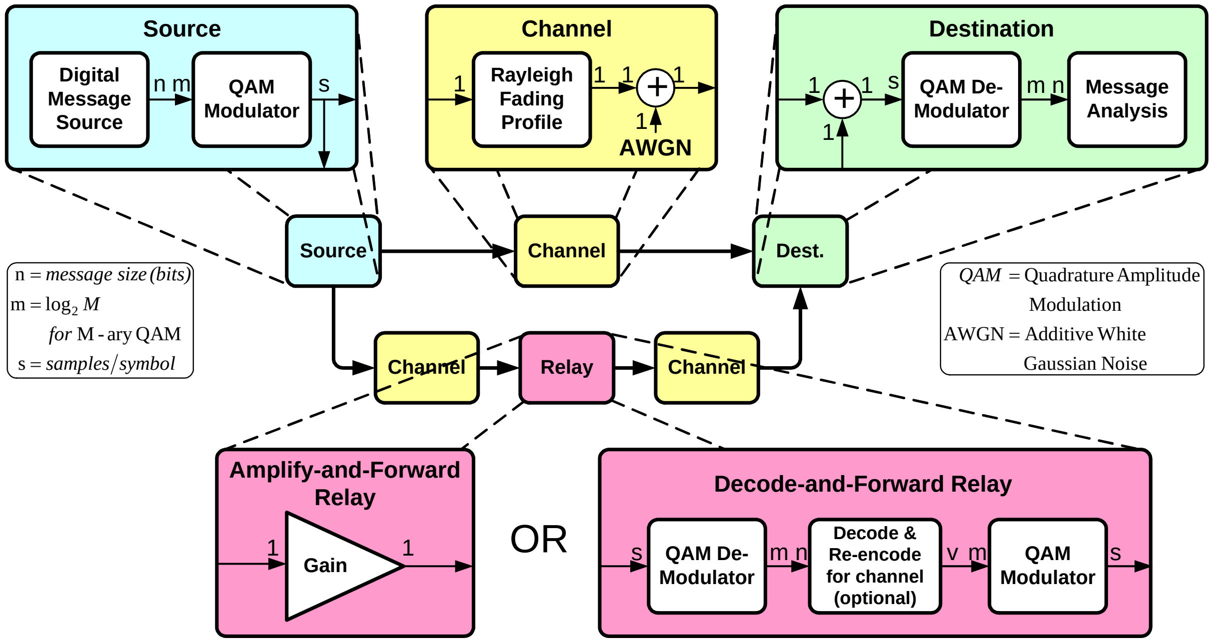

Figure 2: A two-level hierarchical SDF model for the wireless relay channel

The channels shown in Figure 3 are modeled as orthogonal, narrowband wireless channels suffering from slow, frequency nonselective fading and additive noise. The *Rayleigh Fading Profile* block applies a fading profile to the input signal by performing a point-by-point multiply with the profile coefficients. The coefficients are modeled as independent zero-mean stationary complex jointly Gaussian random sequences so that their magnitudes are Rayleigh distributed. The homogenous SDF *Channel* block operates on a single complex baseband sample per iteration.

The *Digital Message Source* in the *Source* block produces a message of *n* bits per iteration and consumes nothing. The output of the message source is input into an *M*-ary Quadrature Amplitude Modulator (QAM) where each *m* input bits are mapped to *s* complex baseband samples of a single QAM symbol.

At the *Destination* node, input arcs carrying faded, noisy complex baseband samples from both the source-destination *Channel* block and the relay-destination *Channel* block are summed; in effect, implementing an “equal gain combiner” with unity gain for each path [11].

The resulting samples are input into a QAM demodulator where the symbol samples are mapped back into bits at a rate of $m/s\ \ bits/sample$. When all n bits of the original message are received, the *Message Analysis* block is enabled.

The *Relay* node can take one of two forms corresponding to the amplify-and-forward and decode-and-forward cooperation schemes. In the amplify-and-forward case, the relay simply applies a gain factor to each of its faded, noisy input samples and produces a single scaled sample at its output. The decode-and-forward relay fully decodes (that is, demodulates) the input samples, and re-encodes (modulates) them before forwarding the samples to the relay-destination *Channel*. If the *Relay* is participating in distributed channel code creation as described in [4,9], the optional channel coder/decoder (codec) is enabled (without breaking the semantics of SDF). The codec consumes n input bits and produces v $\left(\forall v \geq n\right)$ output bits.

4 Implementation

I implement the wireless relay channel using NI's LabView development environment. The system takes the form of a hierarchical dataflow graph composed of a *Source Transmitter*, *Destination Receiver*, an *Amplify-and-Forward Relay* and three independently seeded instances of a *Channel* block that applies both Rayleigh fading and AWGN to transmitted symbols (see Figure 3). The structure of the dataflow graph closely follows that of the SDF model described in Section 3; thus, only key differences are summarized here.

- **Source:** The *Source* block is composed of a pseudo-random binary data generator and a QAM modulator. 16-ary QAM is used in the design along with a Raised Cosine pulse-shaping filter provided by NI's Modulation Toolkit.
- **Destination:** The *Destination* block is composed of a QAM demodulator and a bit error rate (BER) analysis block. The BER block is included for future research efforts. As of

yet, the system memory required to measure a BER on the order of 10^{-6} makes such a measurement prohibitively time consuming.

- **Relay:** An amplify-and-forward relay is implemented. The relay gain is variable.

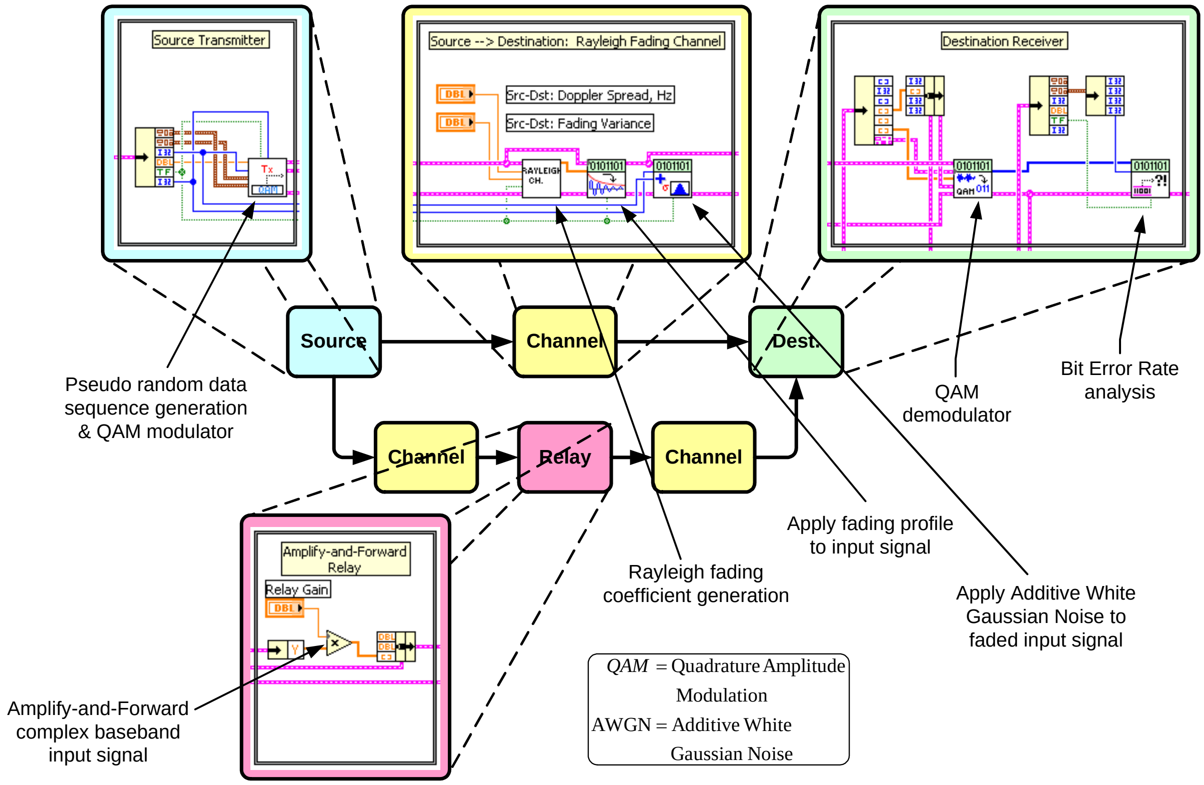

Figure 3: Top-level components of a NI LabView implementation of the wireless relay channel. Here, the relay employs the amplify-and-forward cooperation strategy.

5 Results and Conclusion

The computational complexity of the simulation is summarized in Table 1.

Per QAM Symbol	Real Multiplies	Real Additions
Pulse Shaping (8 taps)	$8 \times 3 = 24$	8
Channel (x3)	9	6
Combiner	0	2

Table 1: Computational complexity of processing a single QAM symbol

The figures in Table 1, however, only represent the datapath processing. The complexity is greatly increased when analysis and visualization blocks are taken into account and the traditional tradeoff between data visibility and verboseness vs. simulation complexity applies.

Figure 4 shows the instantaneous signal power at the output of an example simulation run. Note that the combined power still experiences a –50 dB event as the source and relay paths are not completely uncorrelated in this example.

The modeling framework and LabView implementation provide a solid foundation for continued research in cooperative diversity. The simulations and tools developed in this work can be reused and extended in order to develop new cooperation strategies and protocols.

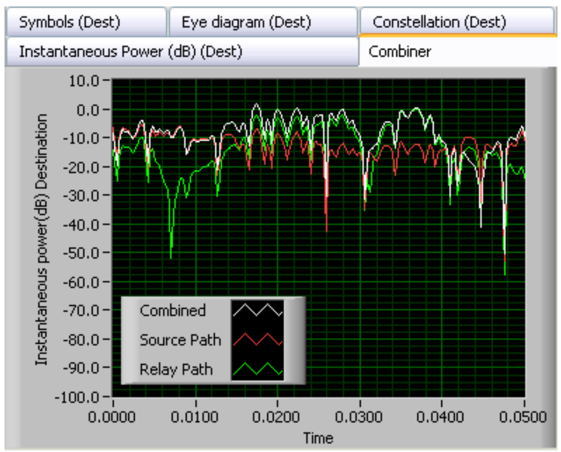

Figure 4: Instantaneous power of *Source* path (Red), *Relay* path (Green) and their equal weight combination at the receiver (White). Note the improvement of the combined signal (complex sum) over the individual input paths even when the *Source* and *Relay* paths are not entirely uncorrelated.

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